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Mercury distribution in a massive sulfide ore deposit at Balmat, New York

David Ray Jessey

MERCURY DISTRIBUTION IN A MASSIVE SULFIDE ORE DEPOSIT AT BALMAT, NEW YORK

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Richard W. Hayes (Advisor) Gene Kisvarsanyi

Roger K. Clifford

ABSTRACT

Ore samples consisting of diamond drill core and mine samples, collected from several Balmat ore bodies, were analyzed for their mercury content. The average contents in these ore bodies were found, in ppb, to be: Upper Gleason, 829; Middle and Lower Gleason, 504; Loomis, 546; Fowler, 195; No. 1 Zone, 37; Sylvia Lake, 59; No. 2 Mine, 5. If all of the mercury in these pyrite-sphalerite-galena ores occurs in the sphalerite, then the average sphalerite mercury contents, in ppb, are the following: Upper Gleason, 2490; Middle and Lower Gleason, 2516; Loomis, 2701; Fowler, 1376; No. 1 Zone, 384; Sylvia Lake, 408; No. 2 Mine, 34. This sequence is the same as that above, in which the lower an ore body occurs stratigraphically the higher its mercury content.

The most interesting feature of the results of this research is an upward stratigraphic decrease in mercury concentration, not only from deposit to deposit upward through the stratigraphic column, but also within a single ore body. The Fowler and No. 1 Zone ore bodies illustrate, particularly well, the upward decrease in mercury in single ore bodies. The Upper Gleason ore body, which is overturned due to folding, exhibits an overturned mercury pattern in which mercury decreases downward. This indicates that the pattern of mercury distribtution was developed prior to folding and metamorphism.

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I. INTRODUCTION

A. Purpose and Scope of the Study

A significant proportion of contemporary literature in economic geology has been devoted to investigations in two important fields: trace element distribution, and the genesis of massive sulfide ore deposits. Unfortunately, however, few attempts have been made to interrelate the two topics. This is particularly true of trace element mercury which is the subject of this thesis. Literature on mercury zonation has dealt mainly with the "mercury halo" as an aid to exploration. Conversely, literature on the genesis of ore deposits, particularly the massive sulfide type, has been devoted to studies of nearly everything, but trace element distribution. This is especially true for the literature of North American economic geology. For this reason, the present study was initiated to determine mercury distribution in a massive sulfide ore deposit at Balmat, New York.

The writer has included additional statistical data on the mercury concentrations of all Balmat ore bodies to provide the staff of the Geology Department at St. Joe Minerals Corp. with some basis to use mercury

as a possible exploration tool.

B. Location and Physiography

The zinc deposits at Balmat, New York were chosen as the study area. One reason for this choice was, of course, the fact that the zinc deposits are a massive sulfide ore deposit. A second reason was the unsurpassed collection of base maps and geologic maps possessed by the Geology Department at St. Joe Minerals.

The mining operations of St. Joe Minerals Corp. at Balmat, New York are easily accessible by paved road from Gouverneur, New York, seven miles to the north. Balmat lies approximately 30 miles due south of the St. Lawrence River and 50 miles east of Lake Ontario (Figure 1). Watertown, the largest city in the region, is located 38 miles to the southwest.

The mines at Balmat are part of the larger Balmat-Edwards district, extending from Edwards, ten miles to the southwest to Balmat and Sylvia Lake. Currently all metal mining activity in the district is limited to four mines of the St. Joe Minerals Corp. This study was confined to the ore deposits at Balmat, but much of the discussion to follow can be applied to the entire district.

The Balmat-Edwards district lies within the northeast-trending Grenville subprovince of the Canadian Shield. The rocks are a series

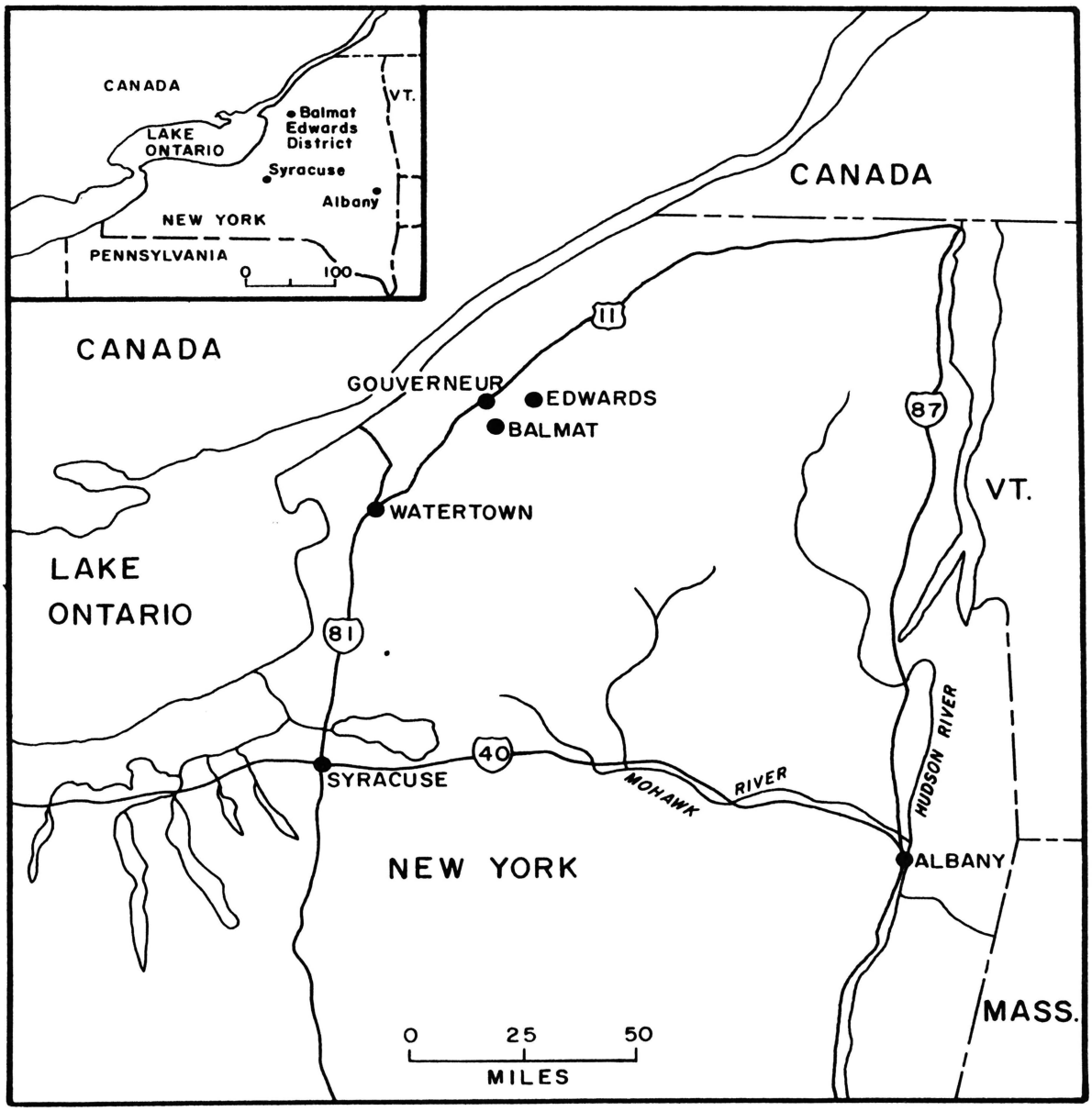

Figure 1. Index map showing the location of the Balmat-Edwards district within New York state (After Lea and Dill, 1968, p. 22).

of highly deformed Precambrian metasediments locally overlain by a thin cover of Cambrian sediments. The boundaries of the district are formed by the flat lying Paleozoic sediments of the St. Lawrence River Valley to the north and the igneous complex of the Adirondack Mountains to the south and east.

Lea and Dill (1968) have offered the following brief account of geologic history. Precambrian time was marked by a period of intense folding and metamorphism. By Cambrian time, erosion had leveled the land surface to that of a gentle relief. Limited depositional activity consisting of terrestrial clastics filling depressions in the karst terrain occurred on the Grenville Marbles during the Late Precambrian and Early Cambrian. In the Late Cambrian the region was invaded by the Potsdam Sea and there followed deposition of perhaps as much as 2,000 feet of Cambro-Ordovician sediments. With regression of the Potsdam Sea in Late Ordovician the depositional history was complete, excepting for minor periods of submergence during recent glaciations. Erosion and glaciation have since worked to restore the land surface to much of its original pre-Potsdam appearance.

C. Acknowledgements

This thesis was supervised by Dr. Richard D. Hagni. St. Joe Minerals Corp. provided the writer with summer employment and an opportunity to collect samples for research. They have also financed

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This writer also wishes to acknowledge a special debt of gratitude to Mr. David B. Dill, chief geologist, St. Joe Minerals Corp., for suggesting the research project and the staff of the geology department; Don Grout, John Kreider, John Johnson and Fred Stone, for their valuable assistance both with sample collection and background information on the mining operations and geology.

II. PREVIOUS WORK

Much of the early work conducted in the Balmat area was of a regional nature, investigating the widespread iron sulfide and iron oxide mineralization. The first papers on the Balmat zinc deposits (Smyth, 1912, 1919; Cushing and Newland, 1925; Smyth and Buddington, 1926; Miller, 1926) were published largely on the mineralogy or regional geology in an attempt to explain the genesis of the deposits.

Later more comprehensive studies of the regional geology by Buddington (1929, 1939, 1948) and Engel and Engel (1953 a, 1953 b, 1958, 1960 a, 1960 b) provide much of the background material used in this paper. A further study by Brown and Engel (1956) summarized the Grenville stratigraphy and structure as it applies to the Balmat area. This paper, although nearly 20 years old, represents the most accurate description of the district's geology. A later paper by Lea and Dill (1968) includes the most recent discussion of geologic setting, but it draws heavily on the earlier works of those above.

Studies of trace elements, excluding mercury, have been conducted

by Doe (1956, 1962). Discussions of mineralogy rely heavily on Lea and Dill (1968), although Brown (1936 a, 1936 b, 1947), Doe (1962), Solomon (1963) and Wiltse (1968) have all included excellent discussions of mineralogy, particularly paragenesis.

Genesis was first discussed by Newland (1917), who felt that the origin of the Balmat zinc deposits could be attributed to either sedimentary or igneous activity, but based on his field observations he strongly favored the latter. Smyth (1918), also relying heavily on field observations, concurred with Newland.

Brown (1936 a) investigated genesis of the Balmat ore bodies and agreed in principle with Newland and Smyth, but pointed out that many of their field observations were not totally correct. Nevertheless, Brown felt the ore deposits were most certainly of the hydrothermal replacement type. Brown (1947) later altered his views slightly and concluded that the ore deposits were not the result of replacement by hydrothermal solutions, but metal rich vapors.

Doe (1956) concluded from a study of sphalerite geothermometry that the temperature of formation of the ore deposits was between 325 degrees and 550 degrees and that the deposits, therefore, belonged in the hypothermal-hydrothermal class.

In the 1950's and early 1960's the volcanic syngenetic theory of

genesis for massive sulfide ore bodies became a subject of attention, due especially to the efforts of Stanton (1960), Kinkel (1962), Hutchinson (1965), Anderson (1958, 1969), Suffel (1965) and others too numerous to name. Solomon (1963) offered a variation of the syngenetic theory as an explanation of genesis at Balmat. He concluded the ore deposits were certainly syngenetic, but not necessarily volcanic. Brown (1965), probably influenced by prevailing geologic thought, again revised his earlier beliefs and concluded that on the basis of lead isotope studies the ore bodies were definitely premetamorphic and probably syngenetic.

Wiltse (1968) still favored a hydrothermal origin for the deposits using his study of mineral paragenesis as evidence. Dill (1973 pers. comm.) feels that on the basis of field observations and personal experience as a mine geologist the ore deposits are possibly the metamorphosed equivalent of Mississippi Valley type lead-zinc ore deposits.

Mercury has been employed as a geochemical prospecting tool for over a decade (Hawkes and Webb, 1962; Williston, 1964). Case histories of prospecting on the basis of anomalous trace element concentrations of mercury have been especially common in geological journals of the Soviet Union and are becoming increasingly common in the West (Brokaw et al., 1962; Friedrich and Hawks, 1966).

The presence of mercury in sphalerite was reported as early as 1889 by Bartlett (1889). More recent publications (Fleisher, 1955; Eckel,

1961; Jolly and Heyl, 1968) have attempted a comprehensive compilation of mercury concentrations for a number of sphalerite ore bodies. This writer was unable, however, to find any publication on the possible mercury zonation in syngenetic sulfide ore bodies.

III. SAMPLING AND ANALYSIS

A. Field Sampling

Field samples were collected from existing diamond drill core augmented to the fullest extent possible by mine samples. Mine samples were often difficult to obtain, either because the ore body had been mined out at the point the samples were needed or the writer was unable to locate the necessary sampling locations from old plan maps. Each sample was plotted on its corresponding cross section as it was collected. The number of samples collected from each ore body varied depending upon the size of the ore body, the number of drill holes per section and mine accessibility.

B. Initial Sample Preparation

Each sample was washed as thoroughly as possible with water. This was one of the major problems with sample preparation. It was felt that the use of soap or any chemicals could possibly lead to some mercury contamination so they were to be avoided. However, much of the core dates back 20 to 30 years and it is impossible to determine the effectiveness of a water wash in removing surface and near surface

contamination from storage and drilling fluids. This could explain some of the anomalously high values encountered for drill core samples. Following the wash each sample was allowed to dry overnight before commencement of crushing.

Prior to crushing each sample was inspected with the aid of a binocular microscope and an estimate made of the percentage of sphalerite present. The error in these estimates will vary, but the writer feels it will approximate one to two percent for those samples with less than 15 percent sphalerite and two to four percent for those samples with greater than 15 percent sphalerite.

Each sample was crushed in a small jaw crusher and ground to sieve size in a ball mill. Samples were then sieved and the -70 + 200 mesh fraction retained. This size fraction was chosen after several test runs revealed no significant loss of mercury through grinding above 250 mesh. The relatively fine mesh size also permitted a large surface area for leaching.

C. Laboratory Analysis

The analyses were performed in the geochemistry laboratory of the University of Missouri - Rolla, Geology Department. A Perkin-Elmer Model 303 Atomic Absorption Spectrophotometer with a graph recorder was used to record the sample runs.

The analytical procedure employed is described by Hatch and Ott (1968). Since this procedure has not been previously used in the geochemical laboratory, the writer has included a discussion of minor modifications he was required to make and problems encountered with the method in general. This will be found in Appendix I.

The sensitivity given for the method is 0.1μg/1. Because of the wide range in mercury values for Balmat ore it was necessary to set the graph recorder on a small scale expansion (3x). This small expansion made it impossible to determine concentrations below 1μ g/1. Thus, it is felt that for purposes of this research a sensitivity of 1 μ g/1 or 1 ppb must be taken as the lower limit. Samples with less than 1 ppb were indicated simply as < 1 ppb.

Perhaps, the major criticism of this analytical method is the lack of research conducted on the possible interference effect of other elements. A recent paper by the Geological Survey of Canada (Jonasson, 1973) has dealt with this problem. Although the interference studies were for a different analytical procedure, that procedure bears close enough similarity to the Hatch and Ott method to enable the incorporation of Jonasson's work in this thesis.

Jonasson found that five elements can cause a measurable interference in spectrophotometer readings for mercury; Au, Ag, Pt, Se, and Te. Of these four can be immediately eliminated for Balmat ores.

Jonasson found that a gold content of 12 ppm and a platinum content of 4 ppm per one gram of sample is necessary for significant interference. Gold has not been detected in Balmat ores and a platinum content of 4 ppm would only occasionally be found in some ultramafic rocks, of which there are none in the immediate vicinity of the Balmat mines. Silver and selenium are capable of causing significant interference only at very high concentrations (> 1000 ppm). Doe (1962) found silver contents in fourteen samples of Balmat ore at a maximum of only 50 ppm. Selenium concentrations of > 1000 ppm would be extremely rare for most ore deposits.

Tellurium concentrations of 32 ppm per one gram of sample can cause significant interference. Because tellurium is reasonably abundant in certain base metal sulfide deposits, it was necessary to analyze the Balmat ore. Due to lack of a tellurium atomic absorption tube in the University geochemistry laboratory, a commercial laboratory was selected. The reported concentrations for five samples of Balmat ore averaged < 0.2 ppm, well below the necessary 32 ppm. The deleterious effects of elemental interference should then be at a minimum for atomic absorption determination of mercury in the Balmat ores.

IV. GEOLOGIC SETTING

A. Regional Setting

The Balmat-Edwards district lies to the west of the Adirondack igneous massif in the Grenville Lowlands subprovince of the Canadian Shield (Figure 2A). Within the lowlands three to five major metasedimentary units can be recognized. The differing number of units represents two possible structural interpretations. They form a roughly arcuate pattern trending northeast along the curved flank of the Adirondack massif. Engel and Engel (1953 b) mapped five units. They are from top to bottom: (1) feldsphathic gneiss, (2) upper marble belt, forming the host rock for the ore bodies, (3) quartz-biotite-oligoclase gneiss, (4) siliceous, dolomitic marble and (5) siliceous and gneissic marble. Engel and Engel felt that field mapping of these units indicated the presence of a large "bulbous" anticlorium (Figure 2B). This structure trends northeast and is responsible for northeast strike of the rock units. According to this hypothesis the oldest unit would lie to the northeast and the youngest or uppermost unit would adjoin the Adirondack massif.

Brown and Engel (1956) acknowledged that a second interpretation

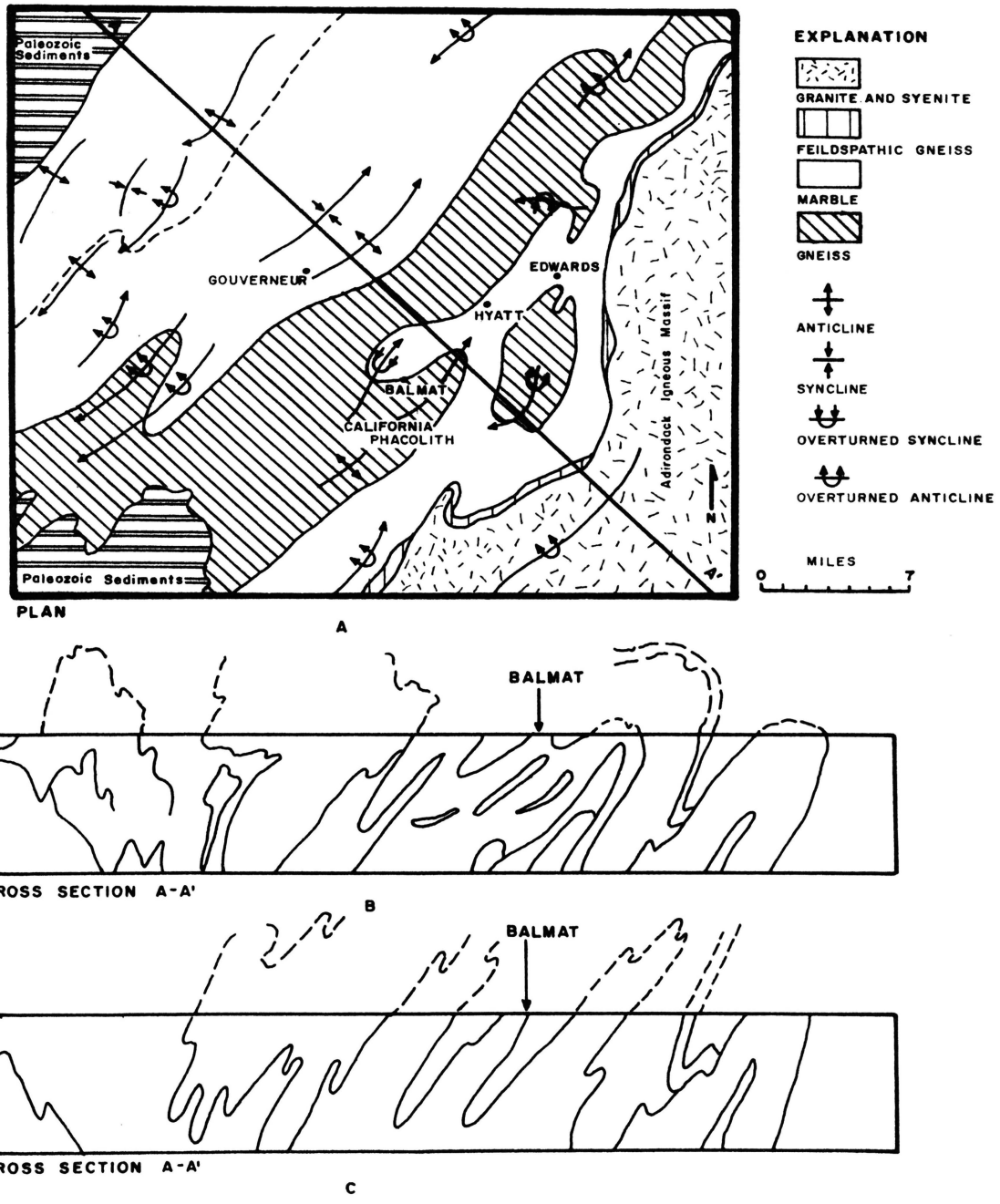

Figure 2. Geologic map of the Balmat-Edwards district and vertical sections along A-A'. Figure 2A geologic map (After Engel and Engel, 1953 b, p. 1056); Figure 2B anticlinorium (After Engel and Engel, 1953 b, p. 1056); Figure 2C isoclinal fold (After Wiltse, 1968, p. 7).

of the structure was possible. Conceivably the marble units 2, 4 and 5 are parts of single unit flanking the sides of an isoclinal fold in the quartz-biotite gneiss (Figure 2C). Both authors, however, favored the original hypothesis.

In either case, the Balmat-Edwards district would be located on the southeast, overturned flank of the structure. This agrees with field observations indicating that the upper marble belt and quartz-biotite-oligoclase gneiss are overturned throughout much of their mappable extent.

A second complexity of the regional structure is the presence of cross folds southeast of the central core of the postulated anticlinorium. Engel (1949) noted that regional mapping indicated that the axes of most mappable folds within the central core trend northeast with the nose of the folds plunging either northeast or southwest at less than 30 degrees. The central segments of the fold axes are very nearly horizontal and consequently the folds are typical components of a regional anticlinorium. Southeastward from this central fold belt, the folds become more complex and difficult to map. It is clear, however, that the gently plunging northeast trending folds have been obiliterated. The fold axes in this belt diverge significantly from the northeast trend of the central belt into a northwest trend similar to dip direction of the rock units. Since these folds lie astride the major structural alignment at a nearly normal angle they take on a steep plunge of 30 degrees-80 degrees to the northwest.

Brown and Engel (1956) termed these folds "cross folds".

The Balmat-Edwards district lies within this belt of cross folds although its western edge is within the transition zone between the cross folds and the central belt of folds. One of the large folds in the district, the California anticline, lies within the transition zone, having a northeast trending southwestern end and a northeastern end that converges in the direction of plunge toward a well defined cross fold. All other major folds in the district show distinct refolding, as for example the Sylvia Lake syncline.

B. Balmat Statigraphy

Early mapping by Buddington (1917), Cushing and Newland (1917) and Brown (1936a) established that the upper marble unit between Balmat and Edwards consists of many distinct lithologic units. Glacial overburden and rock deformation has so obscured these units, however, that it is impossible to map them with any continuity. For this reason only one or two units are normally differentiated during mapping. The most distinctive of these units was named the "median gneiss" by Brown (1936a). It appears to extend from southwest of Edwards to Balmat, but at a point about midway between the two towns it disappears under glacial overburden to surface again near Balmat.

Extensive diamond drilling in the late 1940's enabled the division of the host rock marble unit at Balmat into an additional fifteen units based

on the presence of a very persistent talc-tremolite bed. This subdivision is the one presently used by the geology department of St. Joe Minerals Corp. and employed in the remainder of this paper.

For the sake of brevity a detailed discussion of each lithologic unit will be omitted. Brown and Engel (1956) and later Lea and Dill (1968) provide a comprehensive description of the stratigraphic sequence and the reader seeking additional information is referred to these publications. A discussion of lithology for those units from which the sampling for this paper was done will be found in a later section on lithology of the host rocks.

Basically, the upper marble host rock can be characterized as a series of interbedded calcitic and dolomitic marbles, often highly siliceous. The silica occurs usually in clots or thin beds of quartzite or diopside. Talc and serpentine are found in several units, the products of retrograde metamorphism of tremolite and diopside. Anhydrite, locally altered to gypsum, is present in units 10, 11, 12 and 13.

Units 10 and 13 are of particular importance as "marker beds" because they are easily recognizable in drill cores. Unit 10 exhibits a sea green color, and unit 13 is a talc-tremolite schist. The only non-carbonate-silicate units in the sequence are number 2, a pyritic schist, and number 16 the aforementioned "median gneiss" of Brown.

Engel and Engel (1960 b), based upon the mineral associations of

the upper marble unit and adjacent paragneiss, have determined that the rocks of the Balmat region have reached a metamorphic rank in the almandite-amphibolite facies of regional metamorphism. Further they feel this is be consistent with a metamorphic temperature of 500 degrees-525 degrees and a depth of burial of five miles (1960 a). Northeast of the Balmat-Edwards district metamorphic rank increases, indicating a gradient from southwest to northeast parallel to the trend of the major structural features.

Retrograde metamorphism is common throughout the Grenville Series (Engel and Engel, 1953 a). The talc and serpentine at Balmat are products of retrograde metamorphism as well as chlorite in the paragneiss.

The belief that the paragneiss, quartzite and marble sequence of the Grenville Series represents a normal marine sedimentary sequence has persisted for over a century. Cushing (Cushing, et. al., 1910) stated that the Grenville Series in the Adirondacks represents a typical well sorted marine sequence. Engel and Engel (1953 a) concluded after a detailed study of lithology that the Balmat area was part of a larger basin extending from Grenville, Ontario into the present Adirondack massif. However, due to large scale elemental migrations during Precambrian intrusions and high grade metamorphism it is virtually impossible to reconstruct the original sedimentary sequence.

C. Balmat Structure

The Balmat structural picture is dominated by two major

structural features, the Sylvia Lake syncline and the California anticline, separated by a third and more speculative feature, the Balmat fault zone.

The major fold around Sylvia Lake is most certainly not a simple fold. In broad form it is synclinal, its extension in the form of an isoclinal syncline is inferred to stretch from Balmat to Edwards. However, in the Balmat-Sylvia Lake vicinity the effect of refolding becomes extensive. Northeast of Balmat Corners, the flanks of the syncline flare around the Fowler metagabbro sill (Brown and Engel, 1956). To the southwest of Balmat Corners, the flanks have been fused together and refolded causing the initial syncline to roll clockwise to the northeast. The axis of the refold plunges to the north-northwest producing drag folds with axial planes having a south-southwestern trace and short or disrupted northwestern flanks. Since field mapping indicates several of these folds involve both flanks of the syncline, they are clearly the product of a second generation of folding.

The California anticline is a phacolithic mass of fine-grained granite in quartz-biotite-oligoclase gneiss (Buddington, 1929). Initially the California anticline trended northeast, intertonguing with the Sylvia Lake syncline to the north and a smaller syncline in the marble to the south. During second generation deformation the axis of the California anticline was arched upward markedly, although there is no obvious refold in its axial plane. The arching, asymmetrical to the northeast, has caused a

gentle 15 degrees-20 degrees plunge of the southwestern nose, while the northeastern nose plunges at a much steeper 45 degrees-60 degrees to the northeast (Brown and Engel, 1956). Along the northern edge of the anticline smaller drag folds plunge to the north parallel to refolds in the Sylvia Lake syncline. Presumably both the drag folds and steepened northeastern nose of the anticline formed during cross folding (Brown and Engel, 1956).

The Balmat fault zone was first described by Brown (1936a). Since surface exposures of the actual fault are absent there is no real measure of displacement and hence some debate as to the amount of displacement. There is ample evidence of a northeast trending zone of fractured and cataclastic rock several hundred feet wide and the fault zone does parallel the major shear zones of the cross folding. However, it is possible that any stratigraphic discontinuity might be the result of solid flow and recrystallization. Such discontinuities have been noted in the Edwards area, although they lack the brecciation and cataclasis (Brown and Engel, 1956).

Assuming a displacement by rupture, Brown and Engel (1956) conclude that a dip-slip or strike-slip movement of only 400 to 1500 feet could account for the lithologic discontinuities. Thus, the Balmat fault zone would not seem to be a prominent structural feature, particularly in terms of influencing ore deposition.

One final note of importance is the dominant role that refolds have played in localizing ore bodies. The No. 2 mine is located within a structural crossroads formed by the northeast trending Sylvia Lake syncline and a north-northwest plunging cross fold. The refold in the shape of an isoclinal syncline is the dominant mine structure. The Fowler or No. 4 mine ore body also lies within the belt of refolding although other factors, particularly its location at the nose of the Sylvia Lake syncline, may have been just as important in localization. The Balmat No. 3 mine is located at a structural crossing of the northeast trending drag folds and secondary cross folds plunging to the north-northwest.

The actual effect of a particular cross fold to localize an ore body has little bearing on the present study, but their decided general tendency to be involved in the localization of all ore bodies does have a significant bearing. The obvious conclusion to be drawn from this discussion of localization of ore bodies at structural crossroads is that some migration has been involved. The reader is asked to keep this in mind because it presents one of the most significant conflicts with the results of this investigation to be discussed later.

V. ORE DEPOSITS AND HOST ROCKS

A. Mineralogy

The mineralogy of the ore deposits at Balmat is relatively simple. Brown (1936a) listed sphalerite and pyrite as the major ore minerals with minor amounts of galena and very minor pyrrhotite and chalcopyrite. Doe (1962) added marcasite to the list and Lea and Dill (1968) added realgar and jordanite. Brown (1936b) listed as supergene; willemite, magnetite, hematite and some chalcopyrite, galena and sphalerite.

The gangue minerals described by Brown (1936a) as hypogene include; calcite, dolomite, garnet, diopside, quartz, tremolite, mica, barite, anhydrite, talc and serpentine. In supergene ores chlorite is common with minor garnet.

Lea and Dill (1968) indicate that lateral or vertical zoning is absent. The only change in gross mineralogy is a gradual diminishing of supergene enrichment with depth. These observations are based largely on macroscopic work; microscopic study of the ores might contribute to a better understanding of this aspect.

Other trends in mineralogy seem to be distinct segregation of pyrite, with some ore bodies showing high pyrite to sphalerite ratios and others the inverse. Also, galena tends to occur in the footwall of the localizing ore structures.

B. Host Rocks

The major ore horizons at the No. 2 mine, the "Main" ore zone, the "Streeter" ore zone and the "Hanging Wall" ore zone, are encompassed by the number 14 unit. This unit can be grossly characterized as a quartzose, calcitic marble. Commonly in mapping three sub-units are recognized. Forming the contact with the talc-tremolite schist of the number 13 unit is a light gray dolomite. Overlying the dolomite is a banded, quartz diopside with thin layers of gray, serpentinous dolomite and above that a brown, coarsely crystalline, calcitic marble. The upper third of unit 14 is an undifferentiated sequence of interbedded calcitic marble, diopside, and siliceous, diopsidic marble.

Two smaller ore bodies within the No. 2 mine are the No. 1 Zone in the number 11 unit and the Sylvia Lake Ore horizon along the 11-12 contact. The number 11 unit is a highly siliceous, calcitic and dolomitic marble. Diopside and quartz are particularly abundant near the No. 1 Zone ore body. The number 11 unit at the 11-12 contact is slightly less siliceous with brown, coarse-grained, calcitic marble common. The number 12 unit is a white to gray, coarsely crystalline,

dolomitic marble. Serpentine clots are numerous with minor lenses of quartz and diopside.

The Fowler ore body (No. 4 mine) also occurs within the number 11 unit. The gross lithology differs little from that already described, although massive beds of purple anhyrite are very common. The number 12 unit has been pinched out in the immediate vicinity of the No. 4 mine so that the number 11 unit forms a contact with the talc-tremolite schist of the number 13 unit.

The Gleason ore bodies (No. 3 mine) lie in the number 6 unit. The basal third of the unit is a massive quartzite. The upper two-thirds is less massive with quartzite, quartz diopside and dolomite interbedded. The Loomis ore bodies, also in the No. 3 mine, are localized in the 7, 8 and 9 beds. Unit 7 is a dark gray, fetid, highly graphitic dolomite; unit 8 is an interbedded diopside, quartz diopside and dolomite; and unit 9 is a coarsely crystalline dolomite.

C. Forms of the Ore Bodies

The Balmat ore bodies generally are conformable with the bedding in three dimensions. Lea and Dill (1968) give the following estimate of dimensions:

Thickness: 2 to 50 feet;

Horizontally along the strike: 50 to 800 feet;

Down plunge: Varies, but often very great (up to thousands of feet).

The ore bodies are usually either pod-shaped or tabular. In less highly contorted strata the ore bodies take on a tabular, blanket-like shape, but in more intensely folded rocks they become pod-shaped. The shape and dimensions of the pod-shaped ore bodies are controlled by the secondary cross folds.

Two major factors seem to control the form of ore bodies. One is the presence of cross folds as mentioned above and previously in this thesis. A second is lithology. Sharp contacts of ore with tremolite, calcitic marble and dolomitic marble are common while contacts with serpentinous or diopsidic marble are indistinct. Disseminations and stringers of ore minerals indicate a migration of the ore minerals into these rocks. Contacts of ore bodies with quartzite or quartz diopside are even more irregular showing complex penetrations into the host rock.

VI. STATEMENT AND APPLICATION OF RESULTS

A. Statement

The analytical results for 244 samples from seven ore bodies and eleven cross sections are summarized in Table I. Arithmetic mean, standard deviation, standard error and geometric mean have been calculated for all cross sections. Formulas employed are those available in any standard text on statistics. An explanation of terms that appear in column two of Table I and that will reappear throughout this thesis is necessary.

Ore Hg or Hg in ore is the measurable mercury concentration in an ore sample reported in ppb. % ZnS is the percentage of sphalerite in an ore sample. Total Hg or total Hg in ZnS is the theoretical total value for the concentration of mercury in sphalerite if all the mercury in the ore is contained in the sphalerite. Total Hg is also reported in ppb. The formula used to calculate theoretical total mercury was:

$$\text{Total Hg} = \frac{100}{\%\ \text{ZnS}} \times (\text{ore Hg})$$

For those tables in which averages are given, as in Table I, the above three terms become averages of a number of samples rather than the

Ore Body	No. of Samples	Statistical Subject	Arith. Mean	Standard Deviation	Standard Error	Geometric Mean	Range Low	Range High
Upper Gleason Section #1	23	Ore Hg	486	294	61	420	112	1400
		%ZnS	35.1	13.8	2.9	32.6	12.0	69.6
		Total Hg	1558	1171	244	1291	373	6216
Low/Mid Gleason Section #1	13	Ore Hg	586	273	76	483	< 1	1037
		%ZnS	24.8	14.5	40.0	19.8	4.5	67.5
		Total Hg	3914	3384	940	2441	8	10550
Upper Gleason Section #2	16	Ore Hg	1322	1149	287	916	65	3500
		%ZnS	31.6	13.2	3.3	9.3	9.0	67.5
		Total Hg	3829	3040	760	2489	286	2178
Lower Gleason Section #2	17	Ore Hg	441	328	80	223	1	981
		%ZnS	31.5	21.8	5.3	25.9	10.5	97.5
		Total Hg	1448	1024	250	860	8	3329
Loomis Section #1	22	Ore Hg	546	339	72	378	11	1304
		%ZnS	27.8	17.0	3.6	22.1	4.5	57.3
		Total Hg	2701	2309	492	1741	183	7955
Fowler Section #1	26	Ore Hg	142	146	29	84.5	1	444
		%ZnS	21.0	11.9	2.3	18.2	6.0	58.5
		Total Hg	904	1329	261	275	8	4933

Table I. Arithmetic means, standard deviations, standard errors, geometric means and ranges of concentration of ore Hg (ppb), % ZnS and total Hg (ppb) for each sampled cross section.

Ore Body	No. of Samples	Statistical Subject	Arith. Mean	Standard Deviation	Standard Error	Geometric Mean	Range Low	Range High
Fowler Section #2	34	Ore Hg	236	479	82	70	4	2150
		%ZnS	15.0	12.0	2.0	12.0	4.5	60.0
		Total Hg	1878	3833	657	574	26	17915
Fowler Section #3	26	Ore Hg	132	164	32	66	4	755
		%ZnS	21.1	15.0	3.0	16.4	4.5	60.0
		Total Hg	724	698	137	432	26	3222
No. 1 Zone Section #1	21	Ore Hg	37	30	6.6	22.5	1	122
		%ZnS	10.2	5.4	1.2	8.8	3.0	22.5
		Total Hg	384	319	70	255	20	1295
No. 2 Mine Section #1	44	Ore Hg	4.6	13.6	2.1	1.8	<1	86
		%ZnS	15.2	9.1	1.4	11.4	3.0	39.0
		Total Hg	33.5	65	9.8	15	3.1	337
Sylvia Lake Plan	22	Ore Hg	59	87	18.5	11	<1	279
		%ZnS	19.7	11.7	2.5	15.9	4.5	37.5
		Total Hg	408	654	139	71	3	2402

Table I. (continued)

value for a single sample. Thus, for example, ore Hg becomes the average measurable mercury concentration for a number of samples from a particular ore body.

Total mercury in the sphalerite is termed a theoretical value. To test the validity of this theoretical concept three samples were separated by magnetic separation and then analyzed. Sample one consisted of approximately 50 percent sphalerite and 50 percent pyrite with virtually no gangue. It was separated into two fractions; sphalerite, and pyrite. Separation was judged to be 95 percent effective. The analytical results showed that 90-95 percent of the mercury was present in the sphalerite fraction. Sample two consisted of 40 percent sphalerite, 25 percent pyrite and 35 percent gangue. This sample was separated into sphalerite, and pyrite-gangue fractions. This separation was less effective because some quartz remained in the sphalerite fraction. Estimation of separation was 85 percent sphalerite and 15 percent gangue in the sphalerite fraction, 95 percent pyrite-gangue and 5 percent sphalerite in the pyrite-gangue fraction. Analysis of sample two showed only a small variation from the analysis of sample one. Approximately 85-90 percent of all mercury present was in the sphalerite fraction. Sample three gave less positive results. Sphalerite in sample three amounted to 7 percent, pyrite 10 percent and the remainder gangue. Separation into two fractions was extremely difficult and inefficient. Repeated attempts to reduce the amount of quartz in the sphalerite fraction failed. An estimate of the final

separation showed 35 percent sphalerite and 65 percent gangue (mostly quartz) in the sphalerite fraction, 97 percent gangue and 3 percent sphalerite in the gangue fraction. In this case the 3 percent sphalerite represents a rather large part of the total sphalerite since the gangue fraction was several orders of magnitude larger than the sphalerite fraction. This may explain the poor results which showed only 45 percent of the mercury in the sphalerite fraction and the remainder in the gangue fraction.

Since only three samples were run the results are less than conclusive, particularly for sample number three. A larger number of samples would have provided a basis for a statistical test of the theoretical total Hg in the sphalerite, but the time involved to separate one sample, upwards of twelve hours in the latter case, made this impossible.

Possibly the best test of any assumption or theory is how well it fits the observed results. Trends based on calculation of total mercury in the sphalerite showed the most remarkable results and the frequency with which these trends repeated themselves is virtually impossible to explain by chance.

B. Results

1. Upper Gleason Ore Body

Thirty-nine samples collected from the Upper Gleason ore

body along two cross sections were analyzed.

In cross section the Upper Gleason is a massive pod-shaped ore body becoming more tabular down plunge. Sphalerite is the dominant ore mineral with pyrite accounting for less than two percent of the ore mined. The sphalerite content in this ore body was higher than any other deposit sampled. This cannot be entirely attributed to the fact that the Upper Gleason is a higher grade ore body. The writer believes that the massive nature of this ore body made high grade sampling easier and thus the appearance of the higher grade for the ore body. The Upper Gleason ore body lies in the basal one-third of unit 6 (Figure 3).

Concentrations in ppb of both mercury in the ore and theoretical total mercury in the sphalerite are plotted on each cross section along with the geology in the immediate vicinity of the ore body. For purposes on interpreting the structure, unit 1 is the oldest lithologically and unit 16 the youngest.

Section #1 through the Upper Gleason ore body shows a distinct upward increase in total mercury in the sphalerite. The same trend for mercury in the ore is much less well defined. It should be noted from Section #1 that the Upper Gleason is overturned, the older number 5 unit lying atop the number 6 unit. Therefore, stratigraphically there is an upward decrease in mercury concentrations.

A close observation of Section #1 will show certain anomalous

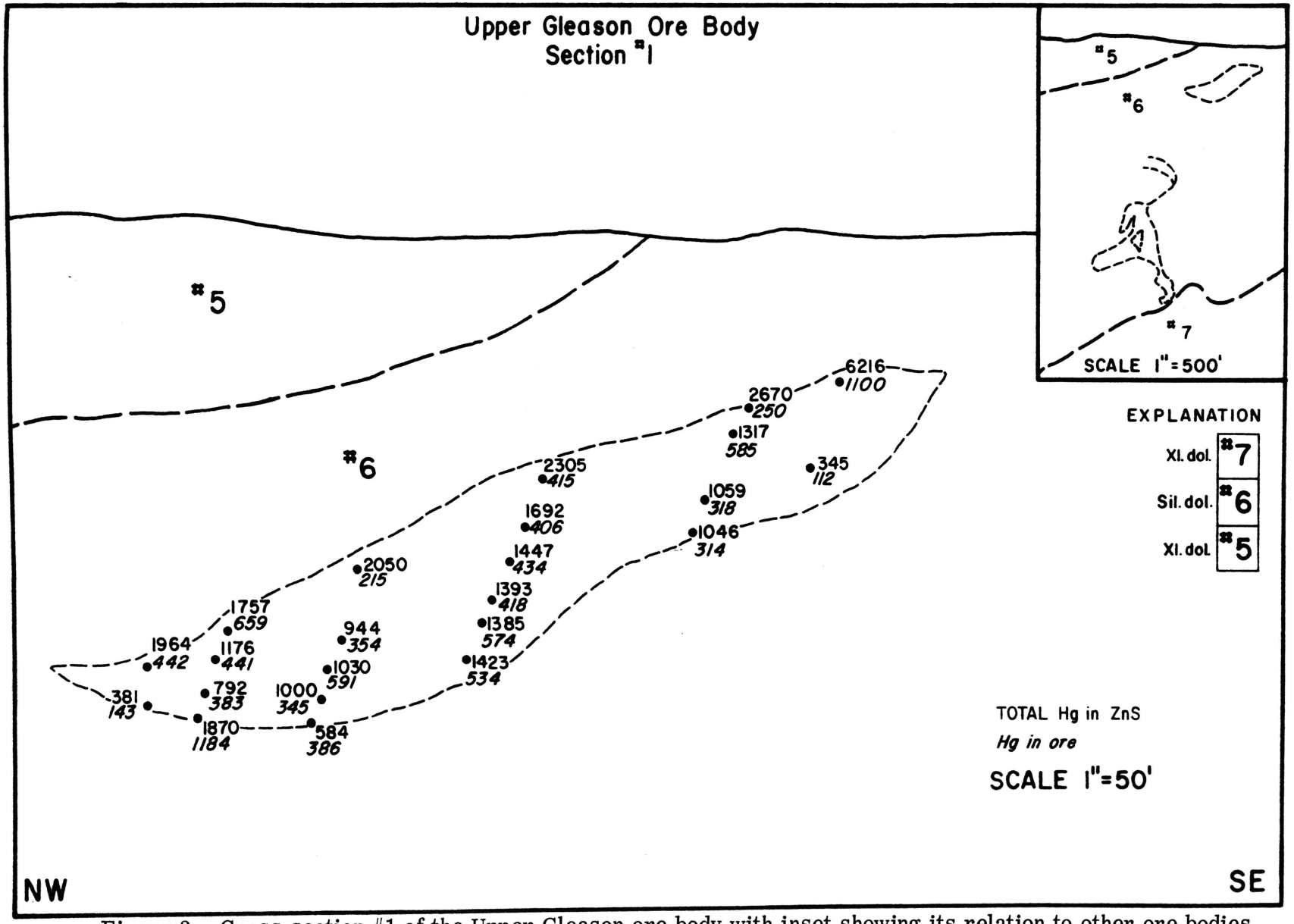

Figure 3. Cross section #1 of the Upper Gleason ore body with inset showing its relation to other ore bodies.

values notably 1870 ppb in the lower northwestern portion of the ore body. These anomalous values, appearing on most of the cross sections, remain unexplained except for an often repeated association of the most anomalous values with the upper or lower contacts of the ore bodies. Other less anomalous values can be attributed to standard error in sampling. Table I gives the standard error for the calculated mean. This also provides a rough, though somewhat high, estimation of the standard error for individual samples.

Since total mercury is a theoretical concept the writer felt it necessary to attempt a statistical correlation to determine the effect of the two major variables upon it. To do this three cross sections showing the best zoning patterns were chosen. The Upper Gleason was one of those.

Table II gives the results of the statistical correlation. Although a correlation between mercury in the ore and percent ZnS would have no effect on total mercury in the sphalerite, for the sake of comparison it was included. For the Upper Gleason Section #1 a comparison of ore mercury in the samples and percent ZnS showed a correlation coefficient of .1728. Correlation coefficients will always lie somewhere between -1 and +1, a plus one value would signify a perfect positive correlation and minus one the opposite. Obviously, a value of zero signifies no correlation at all. Thus, a correlation coefficient of .1728 means an exceedingly poor correlation. The quantity $r^2 \times 100$ gives an estimate of the percentage

Ore Body	Correlation	(r) Coef. Correl.	$r^2 \times 100$	(t)	(t.05)	Est. Conf. Level	d.f. (n-2)
Upper Gleason Section No. 1	Ore Hg/ %ZnS	.1728	3.0	.80	2.080	45	21
	Ore Hg/ Total Hg	.7850	61.6	5.81	2.080	> 1	21
	%ZnS/ Total Hg	-.3900	15.2	1.85	2.080	8	21
No. 1 Zone Section No. 1	Ore Hg/ % ZnS	.6667	44.9	3.93	2.093	> 1	19
	Ore Hg/ Total Hg	.7321	53.3	4.65	2.093	> 1	19
	% ZnS/ Total Hg	-.1420	2.0	.62	2.093	56	19
Fowler Section No. 2	Ore Hg/ % ZnS	.5639	31.8	3.35	2.064	> 1	24
	Ore Hg/ Total Hg	.5255	27.6	3.02	2.064	> 1	24
	% ZnS/ Total Hg	-.2075	4.3	.21	2.064	85	24

Table II. Correlation of the variables ore Hg, % ZnS and total Hg for three cross sections showing a well defined zoning pattern.

of a correlation that can be attributed to the interaction of the two variables considered. In this case 3 percent of any correlation between ore mercury and percent ZnS can be attributed to the influence of one upon the other. A note of caution should be applied here. Most texts on statistics state that any value for r^2 x 100 below 20 percent is highly questionable, indeed some texts question the use of r^2 at all. But for the purposes of this thesis it provides at least a rough estimate of interaction below 20 percent and a much better one above 20 percent.

It is possible to estimate the accuracy of a correlation coefficient by employing the "t" test. From the derived value of "t" and a table of "t's" based on degrees of freedom, the confidence level can then be found. Column 5 of Table II is the calculated value of "t", column 6 is the tabulated value, and column 8 gives the degrees of freedom based on (n-2). Column 7 provides the estimated confidence level. If a confidence level is stated as > 1 this would mean that at least 99 times out of 100 the relationship tested could not be ascribed to chance. Using the comparison of ore mercury and percent ZnS for the Upper Gleason ore body we find a confidence level of 45. This would be the same as saying that 45 times out of 100 any correlation between ore mercury and percent ZnS would be pure chance. To avoid confusion it is often best to think of confidence levels as negative numbers. Thus a confidence level of four would be greater than a confidence level of five and one of > 1 would lie somewhere between one and zero. As a generalization, any confidence level from 0-5 is significant, 5-10 questionable and

below 10 very poor. Returning to the confidence level for the comparison of ore mercury and percent ZnS, 45 is well below 10 and thus there is grave doubt as to the presence of any correlation at all between these two variables, at least for the Upper Gleason.

A comparison of ore mercury and theoretical total mercury in the sphalerite gives a much higher correlation coefficient, .7850, and a confidence level greater than 1. The value for r^2 x 100 is above 60 percent. Thus it would appear that at least for the Upper Gleason, the theoretical total mercury in the sphalerite is greatly influenced by the mercury in the ore, as one would expect for an ore body with a relatively small standard deviation in percent ZnS.

The correlation coefficient for a comparison of percent ZnS and theoretical total mercury in the sphalerite is negative, meaning in effect the smaller the percentage of sphalerite in the sample the greater the mercury concentration in the sphalerite. While this appears difficult to explain, the low correlation coefficient (-.3900) and confidence level of 8 make the comparison itself questionable. The author feels that the explanation of the negative coefficient lies in those samples having only a small percentage of sphalerite. For those samples with less than ten percent sphalerite a difference of four percent or five percent in the estimated sphalerite percentage can cause a significant difference in the multiplier resulting from the division into 100. For example, for a sample with an estimated six percent sphalerite and a sample with an estimated

ten percent sphalerite, within the two percent error for binocular inspection, the difference in the multiplier would be 10 vs. 16.7. Thus, if ore mercury were nearly the same in each sample the value of total mercury in the sphalerite would be larger for the sample containing less estimated sphalerite. Since, as stated above, the estimated percentages for sphalerite are within the sample error, this adds weight to the conclusion that any correlation is probably the result of chance, in this case error in estimation of the percentage of sphalerite.

Upper Gleason Section #2 (Figure 4) is 600 feet down plunge from Section #1. The upward increase in mercury observed in Section #1 appears to be absent. There appears to be a concentric increase in theoretical total mercury outward from the central, more massive core of the ore body, but this is by no means well defined. It is difficult to explain the anomaly between Sections #1 and #2. A partial explanation may lie in the difference in drill holes on the two sections. Drill holes along Section #1 were basically top to bottom, while those along Section #2 were left to right. Therefore, the alignment of samples on Section #2 is much poorer, at least with respect to possible top to bottom zonation.

Table III is a comparison of Sections #1 and #2 for the Upper Gleason ore body, as well as for those other ore bodies for which two or more cross sections were available.

For the Upper Gleason ore body the only significant difference

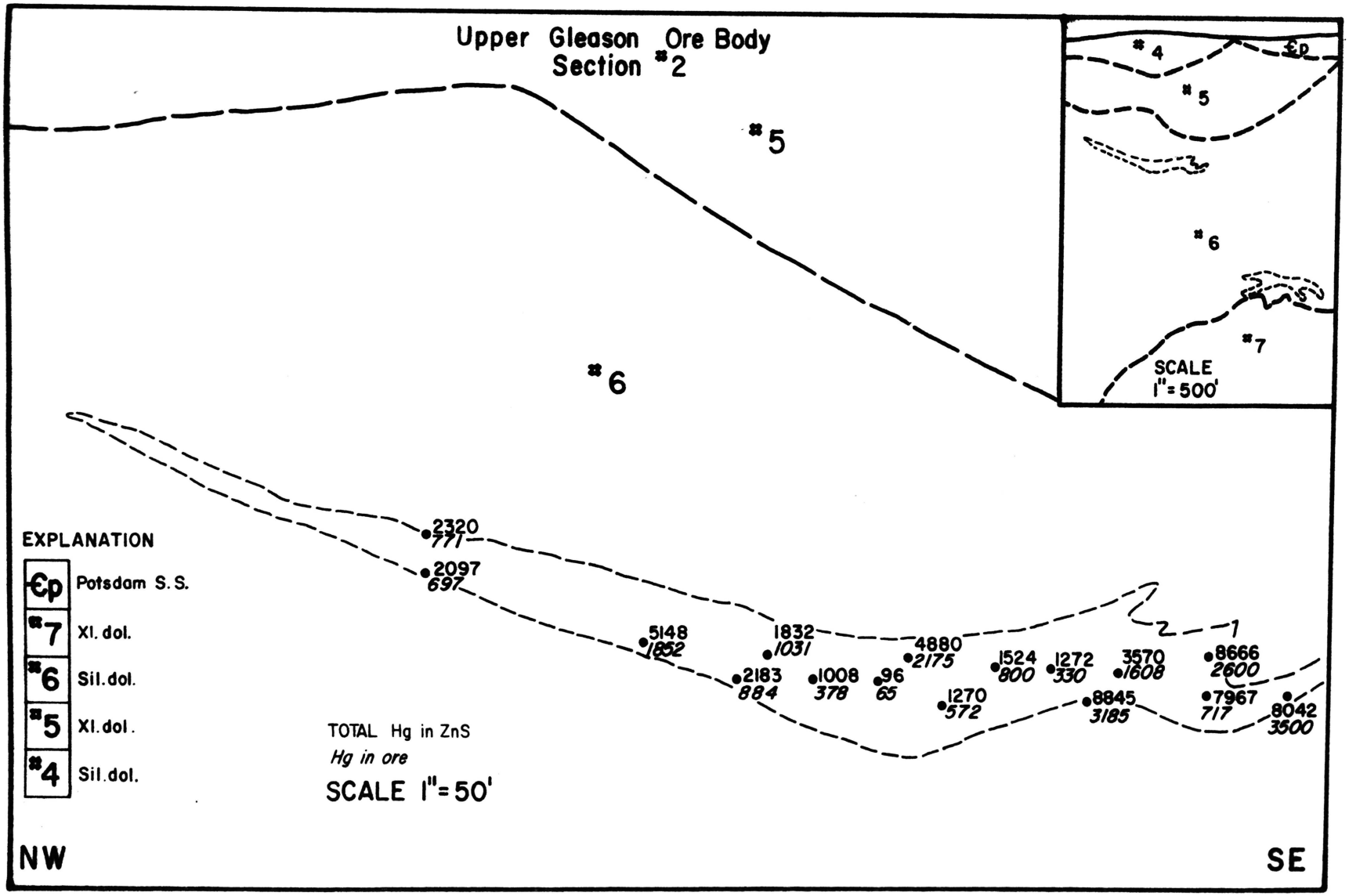

Figure 4. Cross section #2 of the Upper Gleason ore body with inset showing its relation to other ore bodies.

Ore Body	Upper Gleason Section #1	Upper Gleason Section #2	Middle and Lower Gleason Section #1	Lower Gleason Section #2	Fowler Section #1	Fowler Section #2 and #3
A. Mean Ore Hg	486 ± 61	1322±287	586 ± 76	441 ± 80	142 ± 29	230± 71
(t) Ore Hg	3.65		1.29		.976	
% Conf. Level	> 1		22		36	
A. Mean % ZnS	35.1 ±2.9	39.6 ± 3.3	24.8± 4.0	31.5 ± 5.3	21.0 ±2.3	17.7 ± 2.1
(t) % ZnS	1.02		.985		1.02	
% Conf. Level	32		34		32	
A. Mean Total Hg	1558 ± 244	3829 ± 760	3914 ± 940	1448 ± 250	904± 261	1682 ± 570
(t) Total Hg	2.15		2.86		3.05	
% Conf. Level	3.5		> 1		> 1	
(t.05) d.f.=(n-1)	2.042		2.045		2.040	

Table III. A comparison of the cross sections for those ore bodies having two or more sampled cross sections.

between the two cross sections is an increase in ore mercury down plunge; the confidence level at > 1. The confidence level for percent ZnS is well below the acceptable value and that for total mercury in the questionable range.

2. Middle and Lower Gleason Ore Bodies

A total of 30 samples from the Middle and Lower Gleason ore bodies along two cross sections were analyzed.

The Middle and Lower Gleason ore bodies are mapped as two distinct ore bodies, but for the purpose of this thesis they will be considered together. This was necessitated by an overlap of the two ore bodies in one cross section. The Middle Gleason is a massive, cylindrical ore body. It differs from other Balmat ore bodies in its cross-cutting relationship to the enclosing host rock. The Lower Gleason is a pod-shaped to tabular ore body. In many respects it resembles the Loomis ore bodies to be discussed later. Stratigraphically the Middle Gleason, by convention, lies in the approximate center of the number 6 unit. The Lower Gleason lies within the number 6 unit at or near the contact with the number 7 bed. Like the Upper Gleason there is less than two percent pyrite in the minable ore of both ore bodies.

The results exhibited in Section #1 of the Middle and Lower Gleason (Figure 5) are inconclusive. No significant trends appear for either ore mercury or total mercury in the sphalerite. One explanation

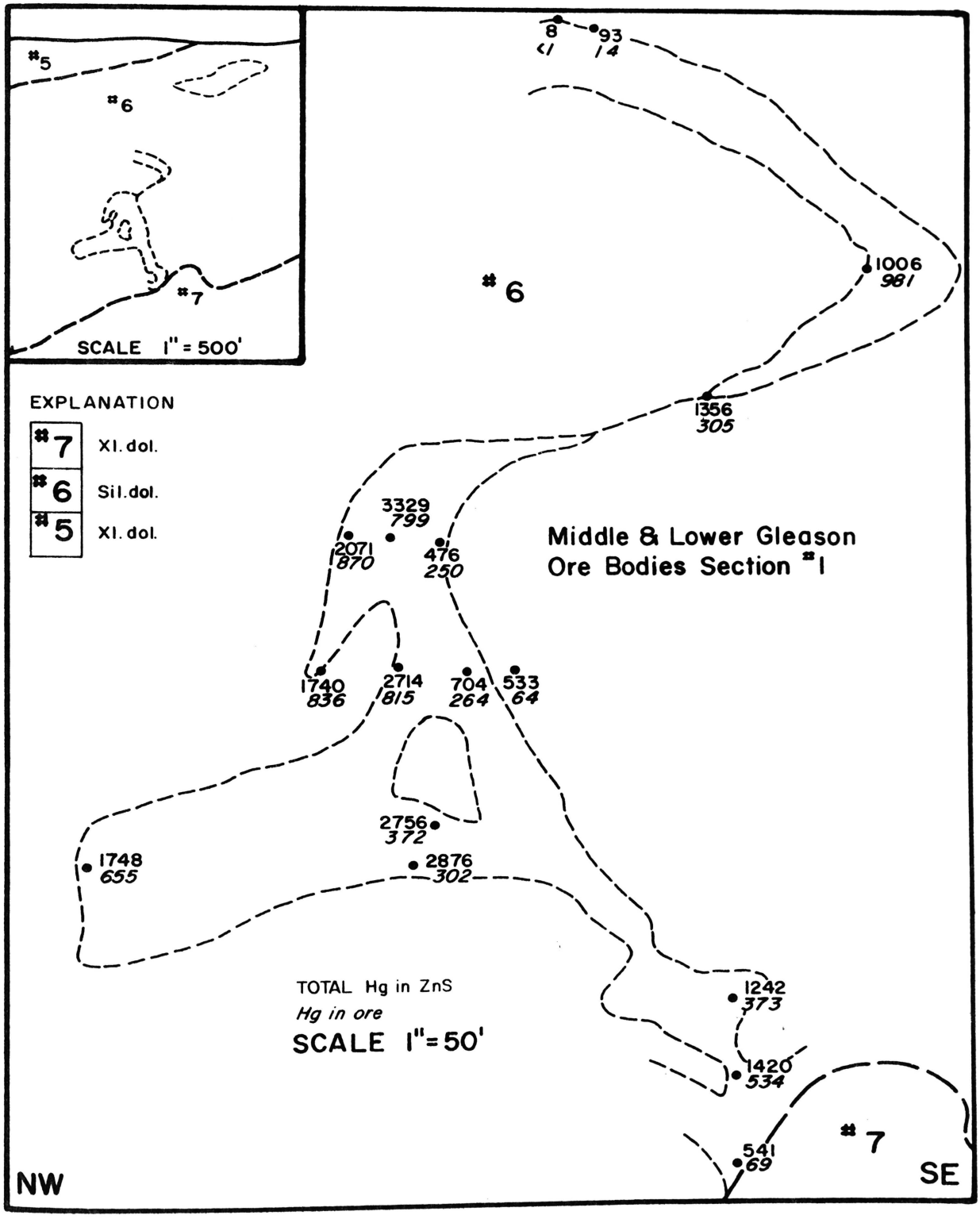

Figure 5. Cross section #1 of the Middle and Lower Gleason ore bodies with inset showing their relation to other ore bodies.

for this apparent lack of definite trends may be the cross cutting relationship of the Middle Gleason. This would seem to indicate a migration of the ore and possibly a masking or homogenizing of any zoning patterns.

The three sample sites in the lower, southeastern corner of Section #1 should be considered in the Lower Gleason ore body. With only these three sample locations no significant statements can be made about the Lower Gleason for this cross section. For the entire section more sample locations would have been desirable, but unfortunately much of the ore had been mined out.

Cross section #2 (Figure 6) exhibits only the Lower Gleason, because the Middle Gleason has been pinched out here. There is no apparent trend for ore mercury, but total mercury in the sphalerite is most interesting. There would seem to be a marked increase in values from northwest to southeast. For the largest ore pod on the northwest side of the cross section there also seems to be the same concentric pattern observed on the Upper Gleason Section #2. It is possible that if samples had been taken further to the northwest they might show the same increase visable to the southeast.

Since a definite increase in mercury in the ore down plunge is present for the Upper Gleason, the Middle and Lower Gleason were also tested (Table III). The results seem to show the opposite of those for the Upper Gleason, a decrease in values. This is not, however, a very

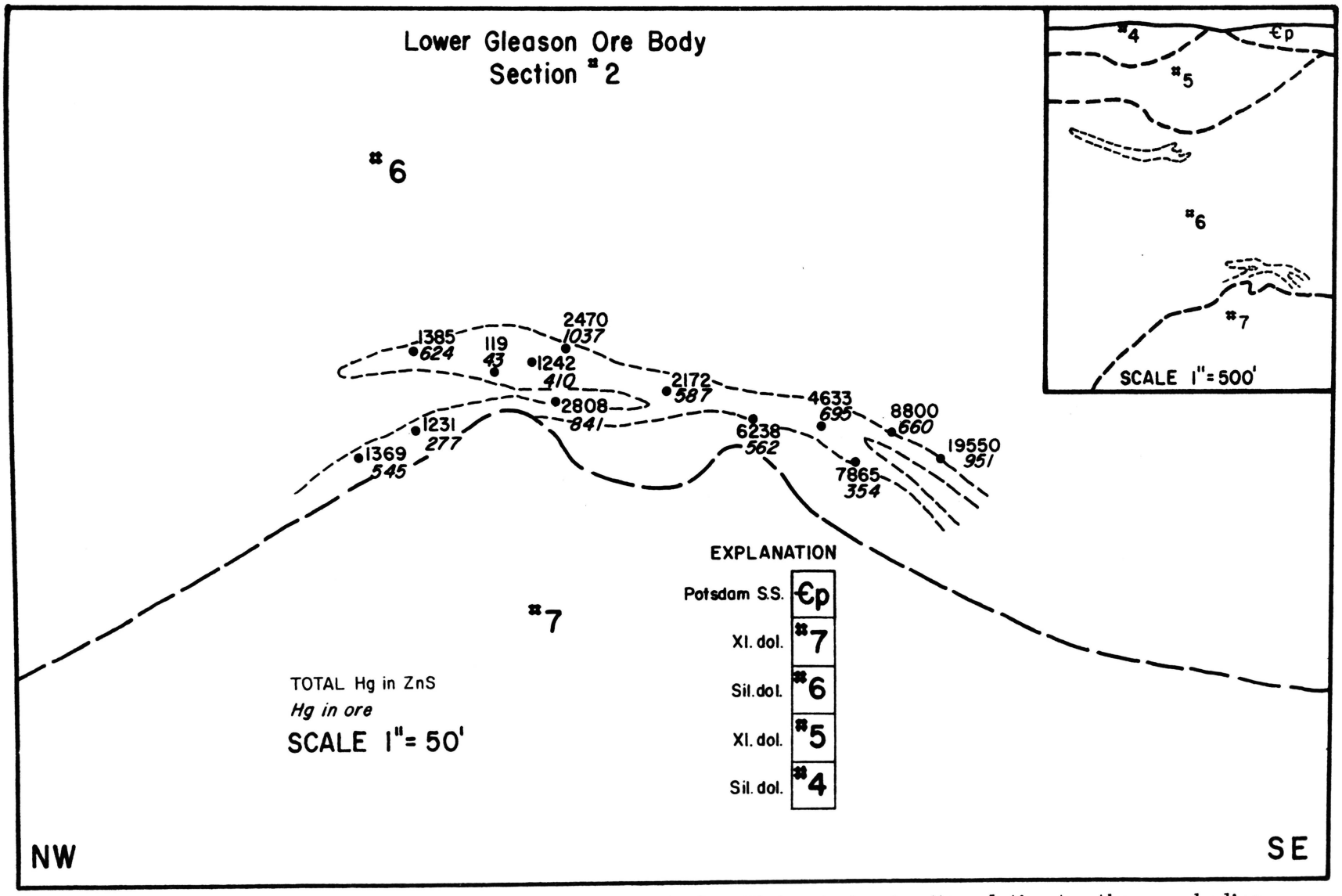

Figure 6. Cross section #2 of the Lower Gleason ore body with inset showing its relation to other ore bodies.

good comparison. Samples on Section #1 were mostly from the Middle Gleason and those on Section #2 from the Lower Gleason. So in reality we are dealing with two separate ore bodies. Moreover, as one can see, the smaller mercury values for the Lower Gleason are in keeping with a trend for a decrease in mercury stratigraphically upward in the Balmat section.

3. Loomis Ore Bodies

Twenty-two samples from a single Loomis ore body were analyzed.

The Loomis ore zone is commonly divided into three separate ore bodies, Loomis A, B, or C depending on stratigraphic position in the number 7, 8 or 9 unit. Unlike the other ore bodies it was most difficult to find a usable cross section. Figure 7 provides some of the explanation. The Loomis ore bodies are tabular to only slightly pod-shaped and generally elongate in profile. Thus, it becomes most difficult to select a cross section with much vertical thickness. For this reason, the writer chose to analyze only one Loomis section.

Similar to that of other No. 3 mine ore bodies, the pyrite content in the Loomis ore is quite low, less than three percent. It should be noted from Figure 7 that because of its position within a fold the Loomis ore body is actually right side up in contrast to the Gleason ore bodies.

The best patterns are shown by total sphalerite mercury.

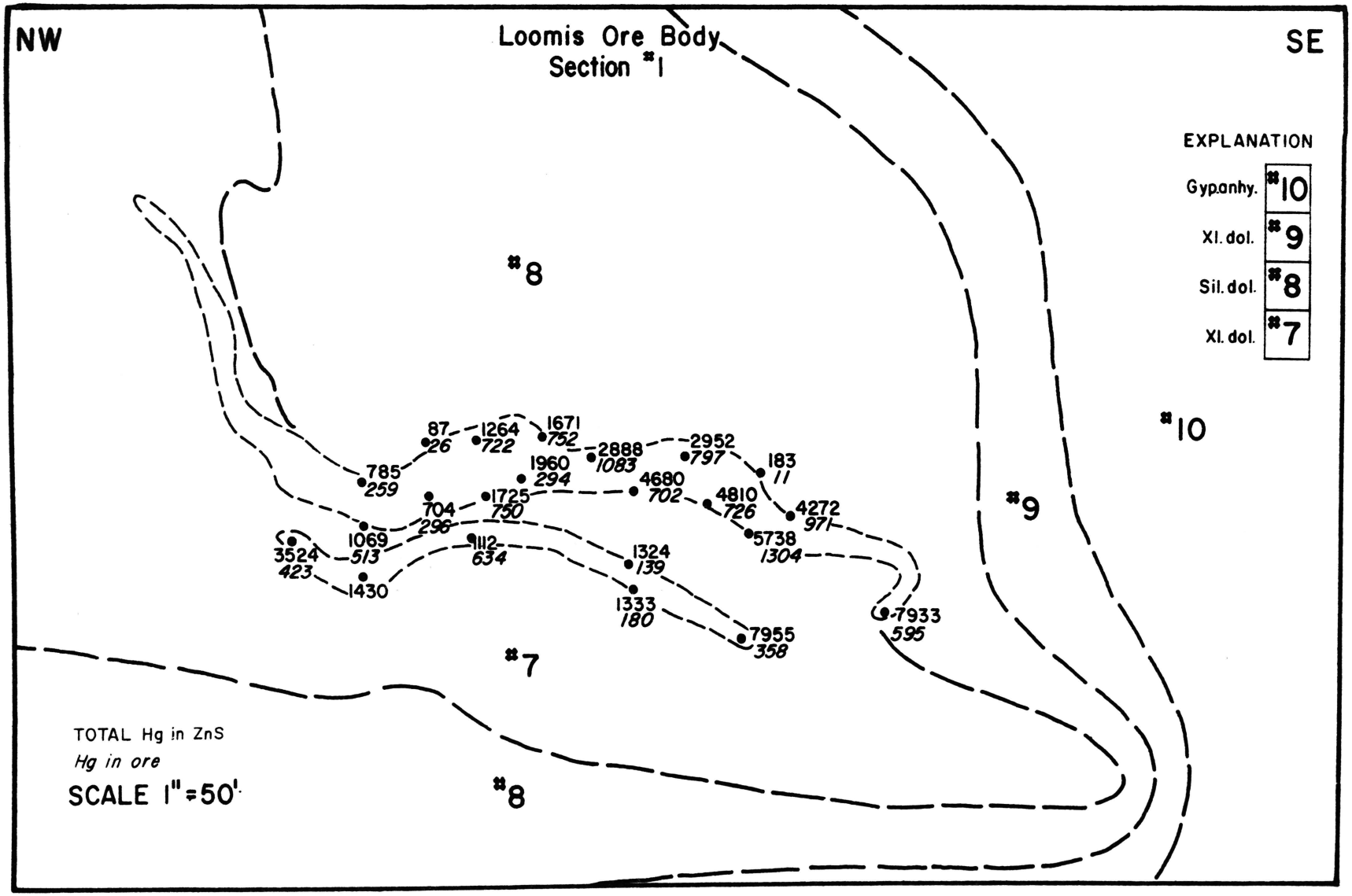

Figure 7. Cross section #1 of the Loomis ore body.

Considering only the two upper ore pods there is a distinct decrease in values from bottom to top. Also, there appears to be the same increase in values in the northwest-southeast direction exhibited by the Lower Gleason Section #2. However, in relating this ore body to the previous Gleason sections we must note that they were overturned, while this ore body is right side up. Therefore the bottom to top decrease in values coincides with the trend for the Upper Gleason. However, the northwest-southeast increase in values now becomes the opposite of that of the Lower Gleason.

If the explanation for the northwest-southeast increase for the Lower Gleason is valid, then perhaps the same may be true for the Loomis. Indeed in the northwest ore pod there does seem to be one low value (87 ppb) in the upper center with concentric increases outward from this value. Additional sampling further to the southeast may reveal a continued concentric increase in values. The smaller ore horizon below the two main ore pods seems to suggest this.

4. Fowler Ore Body

A total of 66 samples distributed along three cross sections through the Fowler ore body were analyzed. Sections #2 and #3 are located 700 feet and 800 feet respectively down plunge from Section #1.

The Fowler ore body (No. 4 mine) is pod-shaped becoming tabular down plunge. It is less massive than the No. 3 mine ore bodies with thin

beds of ore alternating with host rock. Disseminations are common. Pyrite content varies with the individual ore bed, but generally ranges from 5-50 percent. Galena is a very common constituent in the ore. In terms of stratigraphic position, the Fowler ore body is localized in the number 11 unit. Structurally this ore body is in a unique position. It lies at the nose of the Sylvia Lake syncline. The extent to which migration has effected the ore body is uncertain.

Fowler Section #1 (Figure 8) does not show any particularly prominent trends of mercury distribution. Looking at the most massive part of the ore body one can see the same vaguely concentric pattern for total sphalerite mercury that characterized some of the other ore bodies, but in this case the trend is even less well developed. In the stringer zones and more tabular portions of the ore body such a pattern cannot be detected. Since we are looking at the nose of an overturned syncline the weak concentric pattern is also indicative of a poorly developed bottom to top decrease in total sphalerite mercury. In this case bottom to top would be west to east. By and large though, the results from this entire section are inconclusive.

Fowler Sections #2 and #3 (Figures 9 and 10) will be considered together. This is necessitated by an overlap of 20 drill core samples for each section. The drill holes were midway between the two cross section lines. In reconstructing the cross sections an attempt was made to project the sample locations to the point they would actually intersect

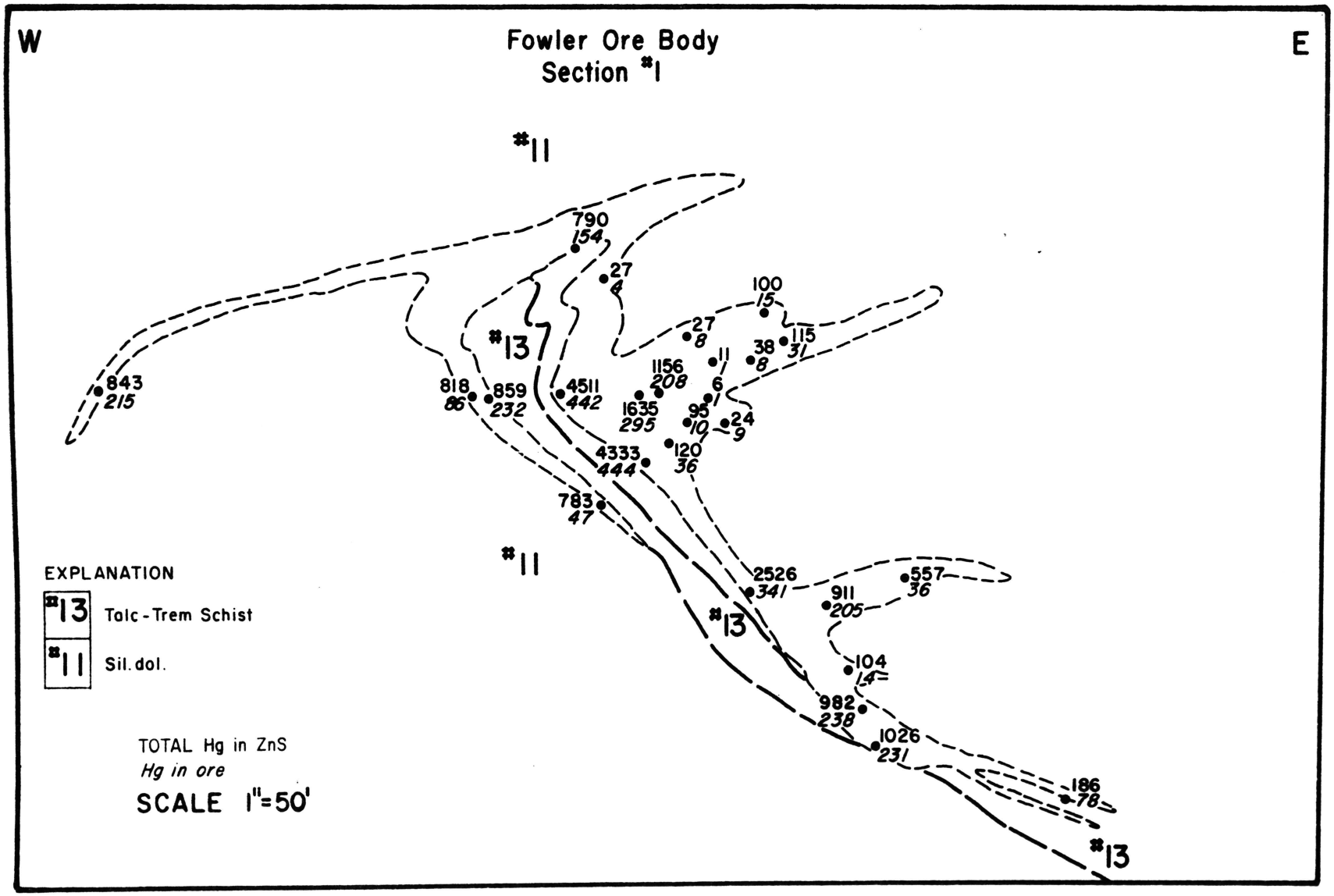

Figure 8. Cross section #1 of the Fowler ore body.

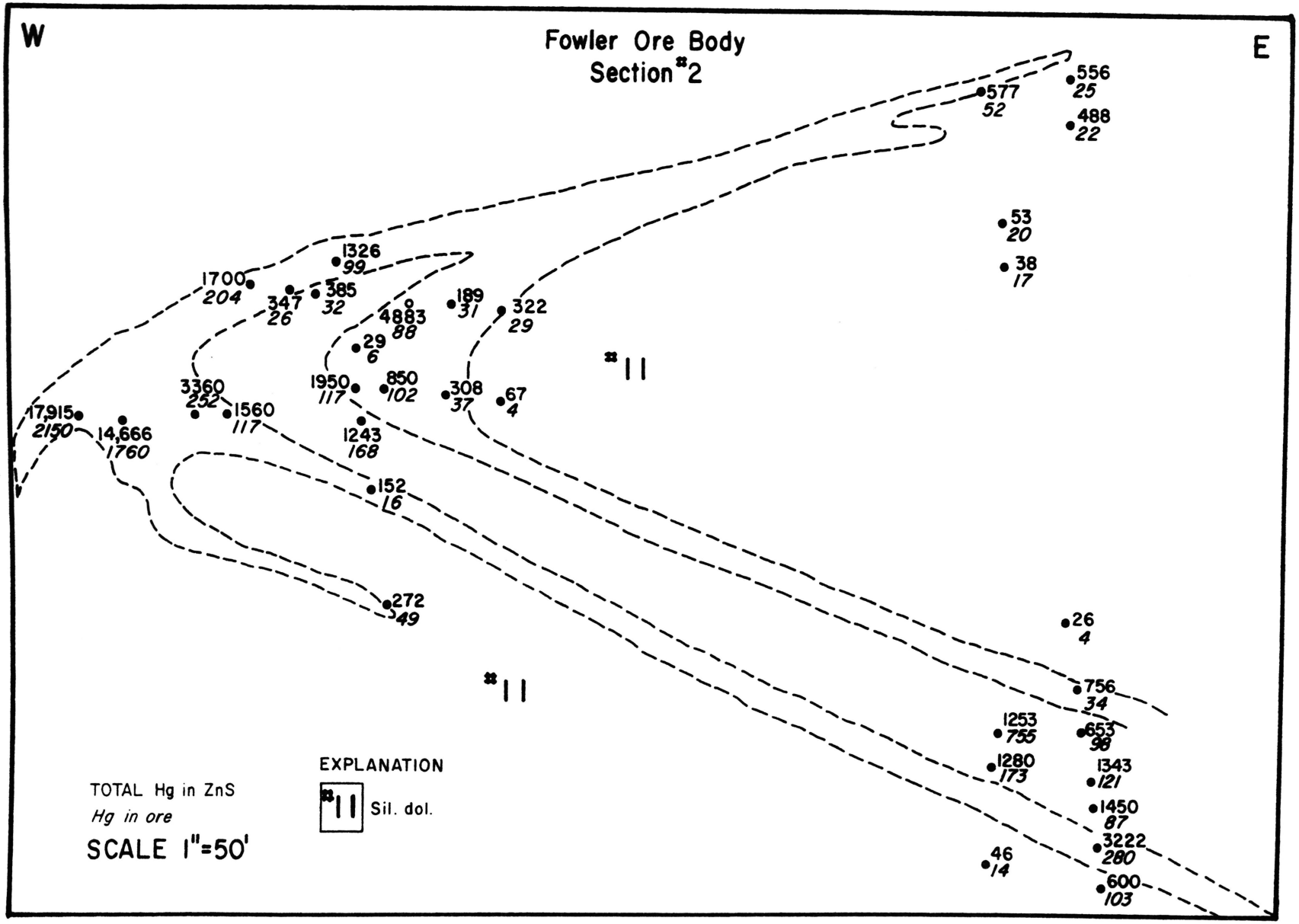

Figure 9. Cross section #2 of the Fowler ore body.

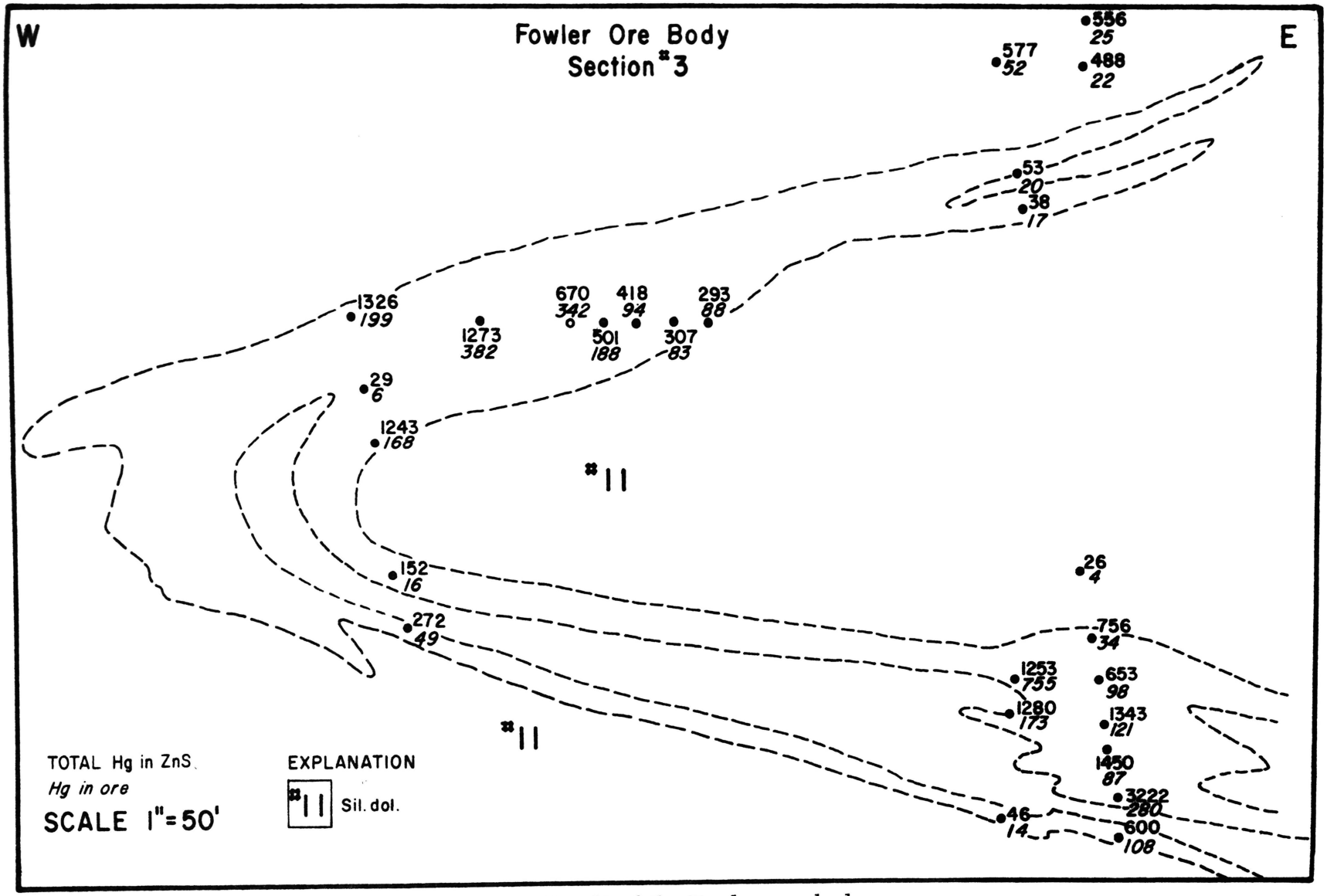

Figure 10. Cross section #3 of the Fowler ore body.

the cross sections.

Both sections show a remarkable bottom to top statigraphic decrease in mercury, particularly total sphalerite mercury. Since the ore body is located at the nose of an overturned syncline, the values on the upper east side of the section increase from bottom to top and those for the lower east side decrease from bottom to top. Even more remarkable is the east to west increase in values at the nose of the syncline. Taken as a whole there is also a noticably semi-concentric increase in mercury from the barren center of the two cross sections.

Since trends in mercury are well developed on Fowler Section #2, it was chosen as one of those to be tested for correlation (Table II). A comparison of ore mercury and percent ZnS showed a correlation coefficient of .5639. Although the confidence level is greater than 1, $r^2 \times 100$ is less than 32 percent. Therefore, we can say that a correlation does exist, but only a poor one. The same holds true for a comparison of ore mercury and total sphalerite mercury. While there is a significant correlation of these two variables for the Upper Gleason Section #1, it is less significant for the Fowler cross section, although the confidence level does exceed 1. A comparison of percent ZnS and total mercury in the sphalerite again yields a negative correlation. In this case the coefficient is only -.1420 and because of the low confidence level no correlation exists between these two variables.

The Fowler sections were also tested to determine if there is a significant increase in mercury down plunge (Table III). Since there is an overlap of samples for Sections #2 and #3 they were considered together. Although the means of both ore mercury and total sphalerite mercury show an increase down plunge, only the increase in total mercury is significant.

The results of statistical tests summarized in Table III are not very conclusive. Only total mercury trends are significant or near significant for all the ore bodies tested; two showing an increase down plunge and one a decrease. However, if one disregards the Middle and Lower Gleason sections, for reasons previously given, then the possibility remains that there is an increase in total mercury down plunge. On the basis of only two comparisons, though, the statement may be inconclusive.

5. No. 2 Mine Ore

A total of 44 samples from the No. 2 mine ore body were analyzed for this study.

The No. 2 mine ore body (Figure 11) consists of three ore zones, the Streeter, Main and Hanging Wall; they will be treated as one ore body for the purpose of this thesis. In terms of size, the No. 2 mine ore body is by far the largest, but unlike the previously discussed deposits it is almost blanket-like in cross section. Individual ore horizons follow and conform closely to bedding and the contacts between host rock and ore

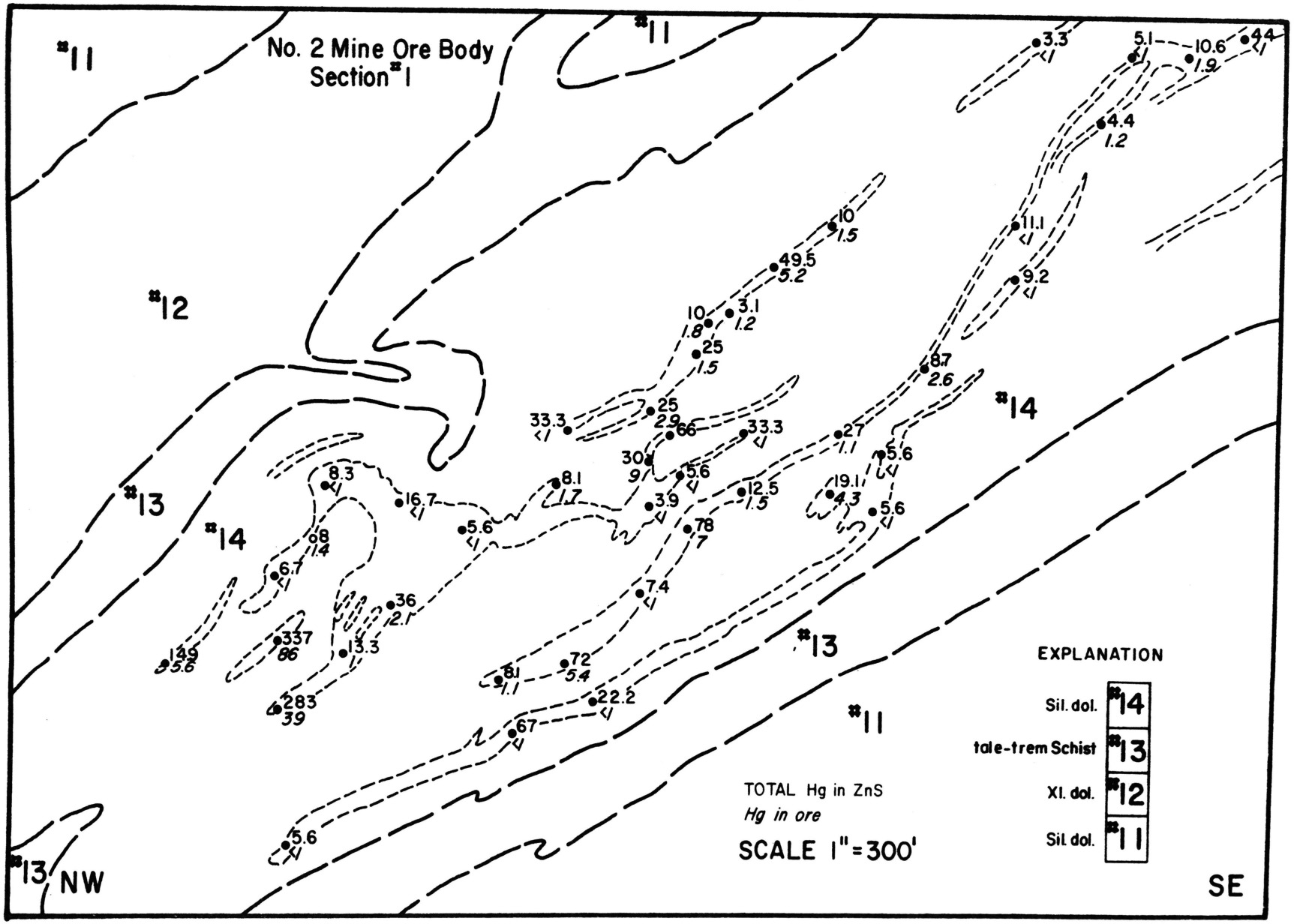

Figure 11. Cross section #1 of the No. 2 mine ore bodies.

often are very sharp.

Stratigraphically the No. 2 mine ore body is within the number 14 unit. Structurally the ore body, like the Fowler, is within the Sylvia Lake syncline. Its position in the syncline provides one of the major problems in interpretation. The ore body is located at the fusion point of the syncline and thus, it would seem that possibly some of the ore horizons are overturned whereas others are not. The pyrite content of this ore body is quite high, exceeding 60 percent of the minable ore in some horizons. Sphalerite percentage for this ore body was significantly lower than that of the No. 3 mine ore bodies. This is more the result of a lack of high grade core samples than an actual difference in the ore grade of the two mines.

The writer can detect no trends for either ore mercury or total sphalerite mercury along the No. 2 mine cross section. This is expected for at least two reasons. One is the difficulty in reconstructing stratigraphic position due to fusion of the syncline, and the second and by far the most important, the extremely low values for ore mercury. Twenty samples were below the detection limit of one ppb and only seven contained greater than five ppb. With nearly half the samples below the detection limit and those in the one to five ppb range questionable, this places a severe handicap on the observation of any zoning. Perhaps the most significant feature of this ore body is its low mean values for both ore mercury and total mercury in the sphalerite (Table I).

6. No. 1 Zone Ore Body

Twenty-one samples collected along one cross section through the No. 1 Zone ore body were analyzed.

The No. 1 Zone (Figure 12)is a small, low grade ore body located in a fold in the number 11 unit. It is pod-shaped in cross section and mineralogically similar to the No. 2 mine ore body. Pyrite content is high. The writer observed that locally pyrite constituted over 80 percent of a mine face. This ore body is mined from the No. 2 mine and although geographically it is positioned close to the No. 2 mine ore body, stratigraphically it is located below that deposit. The ore body occurs in the southeast limb of the Sylvia Lake syncline.

Figure 12 again exhibits a bottom to top decrease in total sphalerite mercury and more vaguely a similar trend for ore mercury. The low grade of this ore body and small standard deviation for percent ZnS (Table I) would require that ore mercury and total mercury in the sphalerite would show a closer relationship than in most other ore bodies. It is also possible to detect a concentric pattern, the barren host rock to the east of the ore body serving as a zero point with concentric increases outward.

Because of the well developed trends, this section was tested statistically for correlation (Table II). A comparison of both ore mercury and percent ZnS, and ore mercury and total sphalerite mercury showed

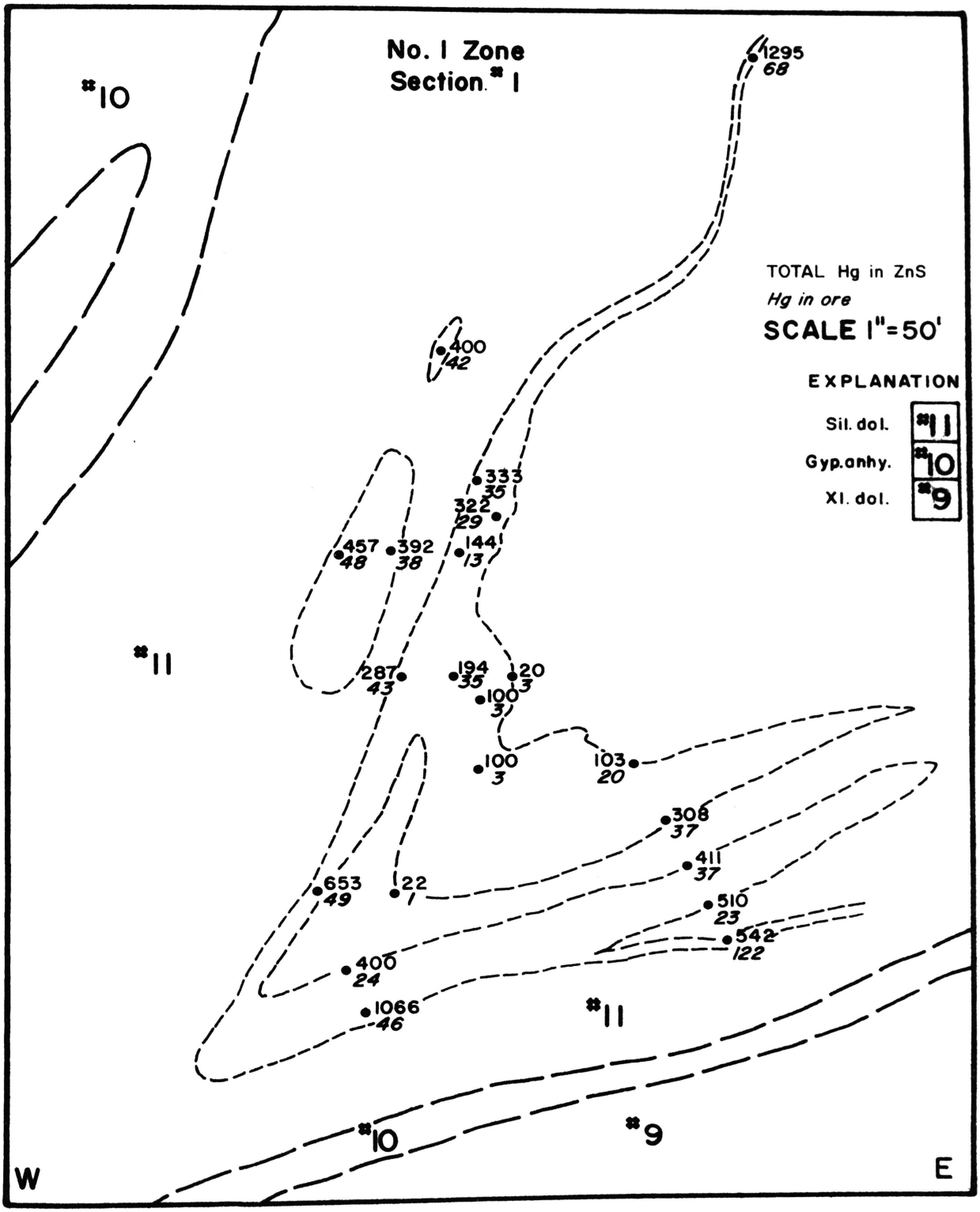

Figure 12. Cross section #1 of the No. 1 Zone ore body.

good correlation. The correlation of ore mercury and total sphalerite mercury is as expected for the reason given. The correlation between ore mercury and percent ZnS is less easy to explain. The coefficient of .6667 is moderately high and the confidence level exceeds 1 so it is statistically significant. Again there is a negative correlation coefficient for percent ZnS and total mercury in the sphalerite, however, the confidence level is quite low and the correlation insignificant. Summarizing Table II, it can be concluded that most certainly mercury in the ore has a great effect on total sphalerite mercury. This would be expected. However, it can also be concluded that ore mercury is not the only factor in determining total mercury. Indeed the values for $r^2 \times 100$ average only about 50 percent. It can also be observed that in two out of three correlations ore mercury was significantly effected by the amount of sphalerite, but it must be noted that in both cases the value of $r^2 \times 100$ is very low. This relationship coupled with the low correlation coefficient for the third cross section casts some doubt upon any significant interaction of these two variables. The negative correlation coefficient for correlations of percent ZnS and total mercury has been previously explained, and there is no correlation between these two variables.

7. Sylvia Lake Ore Horizon

Twenty-two samples from the Sylvia Lake ore horizon were analyzed. Because of the nature of this ore body they were plotted on a

plan map.

The Sylvia Lake ore horizon lies along the contact of the number 11 and 12 units, generally within the number 11 unit. Structurally this ore horizon is within the Sylvia Lake syncline, but the ore body itself is controlled by a small synclinal fold in the 11 unit. This fold takes the form of an elongated trough. The term, "ore horizon", is often used for this ore body because it is minable only at certain points along the strike. In cross section the ore horizon is blanket-like. A plan view was chosen because the thickness of the ore only locally exceeds a few feet and thus, a cross section would not be of great value.

The pyrite content is relatively low, less than 10 percent, but locally it can be much higher. In terms of ore grade it is intermediate between the high grade samples from the No. 3 mine and the low grade samples of the No. 2 mine.

Figure 13 represents a plan view of a part of the Sylvia Lake ore horizon. Plunge is to the northeast. The only trend in mercury distribution that the writer can detect is a vague tendency for the smaller mercury values to be clustered near the center of the ore horizon, within the synclinal trough, with larger values on the flanks. There are a number of exceptions, however. Since this is only a plan view statistical and geological comparisons are not warranted.

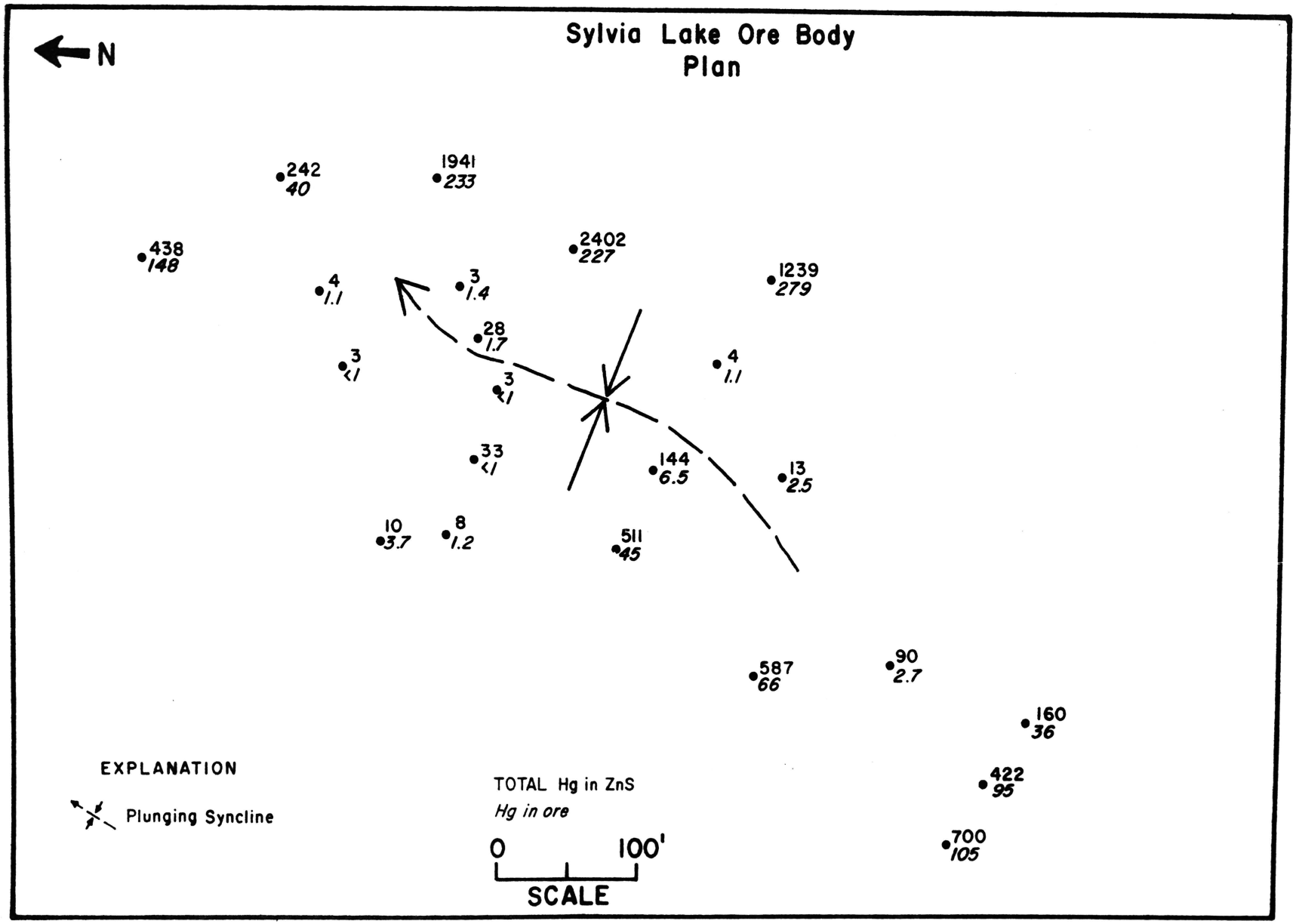

Figure 13. Plan view of the Sylvia Lake ore body.

C. Comparison of the Ore Bodies

No discussion of results would be complete without a comparison of all of the ore bodies. Table IV summarizes the average ore mercury, percent ZnS, total sphalerite mercury and stratigraphic unit for each ore body. For those ore bodies with two or more cross sections a weighted average was calculated.

There is a well defined decrease in both mercury in the ore and total mercury in the sphalerite from deposit to deposit upward in the stratigraphic column. This correlates well with same direction of decrease observed for mercury concentrations within individual ore bodies. One major problem is the possibility of an increase in mercury down structural plunge. The only way to overcome this problem would be to sample a set of cross sections at exactly the same position down plunge. This would be an extremely difficult undertaking since not all cross section are well suited to sampling.

It might be best to determine just how statistically accurate the data is in Table IV. To test the means from Table IV an analysis of variance was made. Table V summarizes the results of this analysis. Table V is divided into three sections, ore mercury, percent ZnS and total mercury. The columns labeled "F" and "$F._{95}$" are the most important. "F" is the calculated frequency distribution and "$F._{95}$" the value at a 95 percent confidence level. This is the converse of "t" values where

Ore Body	Strat. Unit	A. Mean Ore Hg	A. Mean % ZnS	A. Mean Total Hg
No. 2 Mine	14	4.6	15.2	33.5
Sylvia Lake	11-12	59.1	19.7	408
No. 1 Zone	11	37	10.2	384
Fowler	11	195	19.0	1376
Loomis	7	546	27.8	2701
Middle and Lower Gleason	Upper 2/3 6	504	28.6	2516
Upper Gleason	Lower 1/3 6	829	37.0	2490

Table IV. A stratigraphic comparison of the arithmetic means for ore Hg (ppb), % ZnS and total Hg (ppb).

Ore Hg

Source of Variation	Sum of Squares	d.f.	Mean Square	F.	$F._{.95}$
Total	59,536,417	243			
Between Means	21,356,548	6	3,559,424	22.09	2.80
Within Samples	38,179,869	237	161,096		

%ZnS

Source of Variation	Sum of Squares	d.f.	Mean Square	F.	$F._{.95}$
Total	57,718	243			
Between Means	16,444	6	2,741	15.7	2.80
Within Samples	41,273	237	174		

Total Hg

Source of Variation	Sum of Squares	d.f.	Mean Square	F.	$F._{.95}$
Total	1,339,312,282	243			
Between Means	246,489,549	6	41,081,591	8.91	2.80
Within Samples	1,092,822,736	237	4,611,066		

Table V. An analysis of variance of the means in Table IV.

"$t._{05}$" indicates a 95 percent confidence level. As can be seen all calculated "F" values far exceed the tabular value. This means in essence that there is quite a significant difference between means.

Table VI is a comparison of the three variables in an attempt to determine if a relationship among them exists. Statistical terms are the same as those previously used. The correlation coefficients for comparisons of ore mercury and percent ZnS, and ore mercury and total mercury are both quite high. Also, in both cases the confidence level exceeds 1. The high values for the correlation coefficients suggest a near linear relationship. Using the concept of linear regression the writer derived the following two equations for determination of variables:

$$\% \text{ ZnS} = 13.98 + (.0274)(\text{ore Hg})$$

$$\text{Total Hg} = 361 + (3.37)(\text{ore Hg})$$

With these two equations it is possible to make a prediction of both total mercury and percent ZnS for an ore body once the average mercury concentration in the ore is known. Of course, the accuracy of such predictions is in direct proportion to the range of means under consideration. For the Balmat ore bodies this range is great and the values derived from regression equations could easily be 15 or 20 percent above or below the actual value.

The third correlation coefficient is only moderately high (.5358) and the confidence level poor. Therefore, no linear regression study

Correlation	Correlation Coef. (r)	r^2 x 100	(t)	(t. 01)	% Conf. Level	d.f. (n-2)
Ore Hg and %ZnS	.9114	83.1	4.95	4.03	> 1	5
Ore Hg and Total Hg	.9261	85.8	5.49	4.03	> 1	5
%ZnS and Total Hg	.5358	28.7	.1426	4.03	25	5

Table VI. Correlation of the means of the variables ore Hg, % ZnS and total Hg for all Balmat ore bodies.

was attempted.

In general, one can say that ore mercury is influenced by percent ZnS and ore mercury influences total sphalerite mercury. The latter relationship agrees nicely with the results for individual ore bodies and the former agrees to a certain extent. But in both cases the correlation coefficients are a good deal higher for the comparison of a number of means.

VII. SUMMARY AND CONCLUSIONS

The goal of this research was the determination of fundamental statistical data on mercury concentrations for each Balmat ore body. This data is presented both for the use of the mine geologist at St. Joe Mineral Corp. and the economic geologist. It provides the economic geologist with information on mercury concentrations that has heretofore been unavailable for this massive sulfide type of ore deposit.

Table I summarizes mercury concentrations for each cross section analyzed and includes the important statistics of arithmetic mean, standard deviation and range of concentrations. Table IV summarizes the arithmetic mean for each ore body. Since means for mercury concentrations of each ore body vary widely, the writer has arranged the means in Table IV to show this variation stratigraphically.

Within individual ore bodies mercury commonly decreases stratigraphically upward. This distribution pattern is especially well defined in Fowler Sections #2 and #3, and the No. 1 Zone Section #1. A similar, less well defined pattern is shown by Loomis Section #1 and Fowler Section #1. Where beds are overturned, such as in the Upper Gleason Section #1, and where one limb of a folded ore deposit is overturned the

mercury distribution pattern is also overturned, mercury decreasing downward. No stratigraphically controlled increase or decrease occurs in the No. 2 Mine Section #1, and the Lower Gleason Section #2.

The upward stratigraphic decrease in mercury is shown by both mercury in the ore and theoretical total mercury in the sphalerite, the latter accentuating the patterns shown by the former. The extent to which the pattern for theoretical mercury in the sphalerite reflects the pattern of mercury in the ore is a function of the standard deviation of the percentage of sphalerite. For ore bodies with small standard deviations in percent ZnS, i.e. the most uniform ore grade, such as the No. 1 Zone (S.D. = 5.4) the pattern for total sphalerite mercury is quite similar to that for mercury in the ore. On the other hand, for those ore bodies with a large variation in ore grade and hence a large standard deviation in percent ZnS there is a much poorer relationship between ore mercury and theoretical total mercury in the sphalerite. An example is the Fowler Section #2 (S.D. = 12.0) where it can be seen that total theoretical mercury in the sphalerite shows a very remarkable upward stratigraphic decrease, while the same pattern for mercury in the ore is much less distinct.

Since both ore bodies were tested for correlation of variables (Table II), it is easier to understand the relationship between ore mercury and total theoretical sphalerite mercury by comparing the correlation coefficients for each of these two cross sections. The correlation coefficient

(r) for a comparison of ore mercury and total sphalerite mercury for the No. 1 Zone is .73 and that for the Fowler Section #2 is .52. Using the statistic of r^2 x 100 it can be seen that the dependence of theoretical total sphalerite mercury on ore mercury is nearly twice as great for the No. 1 Zone, thus the similarity of patterns for ore mercury and total sphalerite mercury would be twice as great. In summary both ore mercury and theoretical total mercury in the sphalerite show an upward stratigraphic decrease for individual ore bodies, but the trend is generally more distinct for total sphalerite mercury.

Table IV shows that the same upward stratigraphic decrease in mercury occurs from ore body to ore body. The fact that both ore mercury and theoretical total mercury in the sphalerite show this trend equally well is not unexpected since we are now dealing with the mean of a number of samples rather than a few widely ranging individual samples.

The second pattern observed in cross section is a weak concentric zoning. This occurs for the Upper Gleason Section #2, Fowler Sections #2 and #3, No. 1 Zone Section #1, Loomis Section #1, Lower Gleason Section #2, Sylvia Lake Plan and to a lesser extent for the Fowler Section #1. This concentric pattern can be separated into two distinct variations.

The first variation is the concentric or more correctly

semi-concentric pattern resulting from folding. Examples of this pattern are the three Fowler cross sections and the No. 1 Zone cross section. These ore bodies have been folded and the original stratigraphic pattern in which mercury decreases upward has acquired a semi-concentric pattern only as a result of that folding.

The second variation is the concentric pattern in non-folded ore bodies. This is best shown by the Upper Gleason Section #2. This pattern also appears in the Loomis and Lower Gleason cross sections, although in their case the concentric increase is only well shown in one direction, the result of insufficient samples in the other direction. For all of these cross sections there does appear to be an increase in both ore mercury and total sphalerite mercury outward from a thick, massive center toward the thinner flanks. The Sylvia Lake Plan also shows higher values along the flanks of that ore body. The writer is uncertain as to the significance of the concentric patterns. One idea might be that it is a function of the high mobility of mercury, allowing it to migrate to the outer edges of the ore body.

To conclude, the upward stratigraphic decrease in mercury for a single ore body is the pattern to be expected if the ore forming fluid were initially higher in mercury becoming successively depleted with each new period of depositional activity. This stratigraphic zoning of mercury is similar to that of mineralogic zoning so commonly observed for many

of the volcanic-exhalative massive sulfide ore bodies. Furthermore, the upward stratigraphic decrease in the amount of mercury from ore body to ore body indicates that this same depletion occurred over a long period of time.

BIBLIOGRAPHY

Anderson, C. A., 1969, Massive sulfide deposits and volcanism: Econ. Geol., v. 64, p. 129-146.

_____, and Creasey, S. C., 1958, Geology and ore deposits of the Jerome area, Yavapai County, Arizona: U. S. Geol. Survey Prof. Paper 308, 305 p.

Barlett, F. L., 1889, Some notes on the rarer elements found in Leadville sulpurets: Eng. and Mining Jour., v. 48, p. 342.

Brokaw, A. L., Gott, G. B., Mabey, D. R., McCarthy, Howard, and Oda, Uteana, 1962, Mineralization associated with a magnetic anomaly in part of the Ely quadrangle, Nevada: U. S. Geol. Survey Circ. 475, 7 p.

Brown, J. S., 1936 a, Structure and primary mineralization of the zinc mine at Balmat, New York: Econ. Geol., v. 31, p. 233-258.

_____, 1936 b, Supergene sphalerite, galena and willemite at Balmat, New York: Econ. Geol., v. 31, p. 331-354.

_____, 1947, Porosity and ore deposition at Edwards and Balmat, New York: Geol. Soc. America Bull., v. 58, p. 505-546.

_____, 1965, Lead isotopes of pegmatites, granites, and ores: Econ. Geol., v. 60, p. 1167-1184.

_____, and Engel, A. E. J., 1956, Revision of Grenville stratigraphy and structure in the Balmat-Edwards district, northwest Adirondacks, New York: Geol. Soc. America Bull., v. 67, p. 1599-1622.

Buddington, A. F., 1917, Report on the pyrite and pyrrhotite veins in Jefferson and St. Lawrence Counties, New York: New York State Defense Council Bull. 1, p. 1-40.

_____, 1929, Granite phacoliths and their contact zones in the northwest Adirondacks: New York State Mus. Bull. 281, p. 51-107.

_____, 1939, Adirondack igneous rocks and their metamorphism: Geol. Soc. America Mem. 7, 354 p.

_____, 1948, Origin of the granitic rocks of the northwest Adirondacks, in Gilluly, J., Chm., Origin of granite: Geol. Soc. America Mem. 28, p. 21-43.

Cushing, H. P., Fairchild, H. L., Ruedemann, R., and Smyth, C. J., Jr., 1910, Geology of the Thousand Islands region: New York State Mus. Bull. 145, 145 p.

_____, and Newland, D. H., 1925, Geology of the Gouverneur quadrangle, New York: New York State Mus. Bull. 259, 122 p.

Doe, Bruce R., 1956, Geothermometry at the Balmat No. 2 mine, New York: unpubl. Masters Thesis, University of Missouri - Rolla, 56 p.

_____, 1962, Distribution and composition of sulfide minerals at Balmat, New York: Geol. Soc. America Bull., v. 73, p. 833-854.

Eckel, E. B., 1961, Minerals of Colorado, a 100-year record: U. S. Geol. Survey Bull. 1114, 399 p.

Engel, A. E. J., 1949, Studies of cleavage in the metasedimentary rocks of the northwest Adirondack Mountains, New York: Am. Geophys. Union Trans., v. 3, p. 767-784.

_____, and Engel, C. G., 1953 a, Grenville series in the northwest Adirondack Mountains, New York, Pt. 1, general features of the Grenville series: Geol. Soc. America Bull., v. 64, p. 1013-1047.

_____, _____, 1953 b, Grenville series in the northwest Adirondack Mountains, New York, Pt. 2, origin and metamorphism of the major paragneiss: Geol. Soc. America Bull., v. 64, p. 1049-1097.

_____, _____, 1958, Progressive metamorphism and granitization of the major paragneiss, northwest Adirondack Mountains, New York, Pt. 1, total rock: Geol. Soc. America Bull., v. 69. p. 1369-1413.

_____, _____, 1960 a, Progressive metamorphism and granitization of the major paragneiss, northwest Adirondack Mountains, New York, Pt. 2, mineralogy, with analysis of trace elements by A. A. Chodos and E. Godijn: Geol. Soc. America Bull., v. 71, p. 1-57.

_____, _____, 1960 b, Migration of elements during metamorphism in the northwest Adirondack Mountains, New York, Art. 212: U. S. Geol. Survey Prof. Paper 400-B, p. B465-B470.

Fleischer, Michael, 1955, Minor elements in some sulfide minerals, in Bateman, A. M., ed., Economic Geology, 50th Anniversary Volume, 1905-1955: Urbana, Ill., Econ Geology Pub. Co., p. 970-1024.

Friedrich, G. H., and Hawkes, H. E., 1966, Mercury as an ore guide in the Pachuca-Real del Monte district, Hidalgo, Mexico: Econ. Geol., v. 61, p. 744-753.

Hatch, W. R., and Ott, W. L., 1968, Determination of sub-microgram quantities of mercury by atomic absorption spectrometry: Anal. Chem., v. 49, p. 2085-2086.

Hawkes, H. E., and Webb, J. S., 1962, Geochemistry in mineral exploration: New York, Harper and Row, 415 p.

Hutchinson, R. W., 1965, Genesis of Canadian massive sulphides reconsidered by comparison to Cyprus deposits: Can. Inst. Mining Met., Trans., v. LXVIII, p. 286-300.

Jolly, J. L., and Heyl, A. V., 1968, Mercury and other trace elements in sphalerite and wallrocks from Central Kentucky, Tennessee and Appalachian zinc districts: U. S. Geol. Survey Bull. 1252-F, 29 p.

Jonasson, I. R., Lynch, J. J., and Trip, L. J., 1973, Field and laboratory methods used by the Geological Survey of Canada in geochemical surveys; No. 12, mercury in ore, rocks, soils, sediments and water: Geol. Surv. Can. Paper 73-21, 22 p.

Kinkel, A. R., 1962, Observations on the pyrite deposits of the Huelva district, Spain, and their relation to volcanism: Econ. Geol., v. 57, p. 1071-1080.

Lea, Edgar R., and Dill, David B., 1968, Zinc deposits of the Balmat-Edwards district, New York in Ore deposits of the United States, 1933-1967: New York, A. I. M. E., p. 20-48.

Miller, W. J., 1926, Origin of pyrite deposits of St. Lawrence County, New York: Econ. Geol., v. 21, p. 65-67.

Newland, D. H., 1917, The zinc-pyrite deposits of the Edwards district, New York: New York State Defense Council Bull. 2, 72 p.

Solomon, P. J., 1963, Sulfur isotopes and textural study of the ores at Balmat, New York, and Mount Isa, Queenland: unpbl. Ph.D. Thesis, Harvard University, 162 p.

Stanton, R. L., 1960, General features of the conformable pyritic ore bodies, Part I - Field association; Part II - Mineralogy: Can. Inst. Mining Met., Bull., v. 53, p. 24-74.

Suffel, G. G., 1965, Remarks on some sulphide deposits in volcanic extrusives: Can. Inst. Mining Met., Trans., v. 68, p. 301-307.

Smyth, C. H., Jr., 1912, On the genesis of the pyrite deposits of St. Lawrence County: New York State Mus. Bull. 158, p. 143-182.

_____, 1918, Genesis of the zinc ores of the Edwards district, St. Lawrence County, New York: New York State Mus. Bull. 201, 41 p.

_____, and Buddington, A. F., 1926, Geology of the Lake Bonapart quadrangle: New York State Mus. Bull. 269, p. 7-106.

Williston, S. H., 1964, The mercury halo method of exploration: Eng. and Mining Jour., v. 165, p. 309-335.

Wiltse, Milton A., 1968, An electron microprobe study of a natural sulfide assemblage occurring at Balmat, New York: unpbl. Ph.D. Thesis, Indiana University, 317 p.

VITA

David Ray Jessey was born on August 13, 1946, in Youngstown, Ohio. He received his primary and secondary education in Struthers, Ohio. His college education was received from Miami University, in Oxford, Ohio and from Youngstown State University, in Youngstown, Ohio where he received the Bachelor of Science Degree in August, 1972.

He enrolled in the Graduate School of the University of Missouri - Rolla in August, 1972, where he has held a teaching assistantship in the Geology Department for the period August, 1972 to May, 1973 and the V. H. McNutt Memorial Fellowship for the period January, 1974 to May, 1974. His employment as an assistant geologist by the St. Joe Minerals Corporation from June, 1973 to August, 1973 was important experience without which this thesis research could not have been accomplished.

APPENDIX I

A Flameless Procedure of Determining Hg in Ores

The reagents and standard solutions to be used are discussed by Hatch and Ott (1968). The present writer made no changes in the procedure described.

The discussion of sample preparation by Hatch and Ott was found to be slightly vague. The writer, through the process of trial and error, feels it is now possible to amend the original sample preparation techniques. The amendments suggested provided the optimum results for the Balmat ores analyzed for this paper. Subsequent researchers, working with different ore types, may find additional changes necessary.

Hatch and Ott call for one to four grams of finely ground sample to be treated with 25 ml. of concentrated H_2SO_4. They offer no estimate of time necessary for this treatment. For Balmat ores 30 minutes seemed to be sufficient. Following the acid treatment three 1 ml. additions of H_2O_2 are made. Hatch and Ott suggest that sufficient time be allowed between each addition for the peroxide to decompose. Addition of peroxide to the sulfuric acid at room temperature produced no noticable

decomposition of the peroxide at all for periods of over one hour. To initiate decomposition it was found necessary to warm each solution gently on a hot plate at 180 degrees F. Following the final addition of peroxide, each sample was returned to the hot plate, heated, and allowed to react vigorously until all the remaining peroxide had decomposed. The final decomposition of all peroxide is easily noticable by an abrupt cessation of very vigorous bubbling. The temperature of 180 degrees F was chosen because it is below the boiling point of sulfuric acid yet high enough to cause a rapid decompostion. Total time for the three 1 ml. additions of peroxide and its decomposition is estimated at 1 1/2 hours per sample. All samples were then refrigerated for 45 minutes followed by the addition of 100 ml. of deionized water and several drops of potassium permanganate solution. At this point it is often necessary to very carefully shake the solution to insure a mixture of the water and sulfuric acid.

The remainder of the anlysis was performed exactly as described by Hatch and Ott.

A major problem with this analytical procedure was its great sensivity. Although this is generally desirable, for the Balmat ore it proved a decided problem. For mercury concentrations above 500 ppb the sample had to be re-run at a dilution. The writer found that some dilutions had to be repeated as many as three times before an accurate value for the sample was obtained.

This appears to have been a result of improper reacidification prior to dilution. Eventually, accurate values were obtained when reacidifying was done in the same proportion as that used for standards, 25 ml. of 18N H_2SO_4 and 10 ml. of 7N HNO_3.